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Evaluation of Geologic CO_2 Sequestration Potential and CO_2 Enhanced Oil Recovery in Kentucky

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Contents

Executive Summary

Kentucky gets approximately 95 percent of its electricity from coal-fired power plants, which produce significant amounts of carbon dioxide (CO_2). In 2005, Kentucky coal-fired plants vented 102.8 million short tons of CO_2 into the atmosphere. The economic vitality of the state will be affected by its ability to develop and apply a portfolio of technologies that will mitigate input of CO_2 into the atmosphere. One technology that has the potential to assist in this challenge is geologic carbon storage, which captures CO_2 at point sources and injects it into deep rock strata that can store it for tens of thousands of years and longer.

Previous studies suggest that Kentucky has the capacity to store up to 1 billion tons of CO_2 in underground strata. By necessity, the capacity calculations are high-level estimates, and consequently, actual capacity remains unproved and even speculative. In addition, other factors such as infrastructure, engineering, and economic and regulatory policy will affect the viability of geologic carbon storage in the state.

This report is divided into five chapters, each addressing specific technical aspects pertinent to geologic carbon storage, which is the overarching theme. Chapter 1 is an introduction and overview of geologic carbon storage and the data needed to evaluate its potential. Chapter 2 is a geologic evaluation of the potential to use CO_2 for enhanced oil recovery. Chapter 3 is an evaluation of subsurface formation-water geochemistry and implications for CO_2 sequestration. Chapter 4 is an evaluation of CO_2 storage potential with an emphasis along some of the state's major river corridors. Chapter 5 is a geologic evaluation of CO_2 storage potential for nominated coal-to-liquids (gasification) sites.

Chapter 2, "Assessment of Kentucky Fields for CO_2-Enhanced Oil Recovery," analyzes 70 oil reservoirs in 51 oil fields in eastern and western Kentucky for their suitability for enhanced oil recovery (EOR) using CO_2. The relationship among calculated pressures, such as minimum miscibility pressure and fracture pressure, and measured original reservoir pressure, was analyzed and showed that most of Kentucky's oil fields were underpressured even before depletion from production. Nevertheless, if fields are repressurized to values equal to maximum reservoir injection pressures (0.8 psi/ft) as designated by the U.S. Environmental Protection Agency, then 53 percent of the fields could attain miscible or near-miscible conditions. Although the elevated pressures and miscibility would be a transient condition, it could serve to augment additional recovery of oil. In addition to pressure, other reservoir parameters were analyzed to estimate the EOR potential of the fields relative to each other. The fields were broadly ranked into quartiles, and 83 percent of the 18 fields-reservoirs in the uppermost quartile occurred in Mississippian Chesterian sandstones in western Kentucky. Sixty-seven percent of the upper-quartile fields occurred at depths of 1,500 ft or deeper. The chapter concludes with a brief discussion of other issues that affect the viability of a potential CO_2-EOR or storage project. Chief among these issues is the condition of plugged and abandoned and producing wellbores.

Chapter 3, "Geochemical Characterization of Formation Waters in Kentucky and Implications for Geologic Carbon Storage," details how formation-water chemistry measurements from previously archived data were analyzed in the context of geologic carbon storage. The measurements consisted of 356 discrete analyses, mostly from reservoirs in oil or gas wells located in 12 counties in the Illinois Basin of western Kentucky and 11 counties in the Appalachian Basin of eastern Kentucky. Concentrations of dissolved cations and anions provided in the analysis were used, along with temperature and pressure, as inputs to an equation of state that estimates the amount of CO_2 that can be dissolved in the formation waters. Formation-water chemistry was analyzed because dissolution of CO_2 into water — called solubility trapping — is one of the fastest reactions to occur in the reservoir, and it removes CO_2 as a separate phase (gas or supercritical fluid) that is driven upward by buoyancy forces. The magnitude of dissolution is a function of water chemistry and flow patterns. Our analysis of salinity in a depth and stratigraphic framework shows the likely presence of an aerially extensive seal interval in Upper Ordovician rocks that separate Pennsylvanian, Mississippian, Devonian, and Silurian strata from Ordovician and Cambrian strata into broad hydrogeologic compartments. The interval would represent a primary seal for possible CO_2 storage reservoirs in the Cambrian-Ordovician Knox Group. Though widely varying, measured salinity values (approximately 4,000 to 313,000 mg/L) in Cambrian and Ordovician reservoirs are often significantly less than what is predicted by salinity versus depth trends from shallower Pennsylvanian, Mississippian, Devonian, and Silurian samples. When analyzed with an equation of state for aqueous solutions containing

Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-}, the decreased salinity results in higher CO_2 solubilities (approximately 0.65 to 0.86 mol/kg H_2O) and hence more potential for solubility trapping in Cambrian and Ordovician reservoirs.

Chapter 4, "Geologic Carbon Storage (Sequestration) Potential in Kentucky," summarizes the geology of Kentucky and provides information on the area, depth, characteristics, and available data about the deep, subsurface rock units that might have storage capacity or be important parts of confining intervals for underlying storage reservoirs. Nine units were considered possible storage reservoirs, four units were investigated as confining intervals with local porosity and possibly storage capacity, and six units were investigated as seals. The Mount Simon Sandstone, which only occurs in the northern part of the state, has the largest calculated capacity. The Mount Simon occurs at depths of 3,000 to more than 10,000 ft, but below 6,000 ft may have little porosity. Our research suggests a reduced aerial distribution of the Mount Simon in western Kentucky and an attendant decrease in volume and storage capacity, though still significantly more than in other units. A well drilled in the summer of 2009 tested the Mount Simon at East Bend in Boone County, and provided data demonstrating the feasibility of using the Mount Simon for CO_2 storage in Kentucky.

Additional units have capacity that is more difficult to quantify. The Devonian black shale is Kentucky's primary natural gas producer. Experimental studies suggest that the Devonian shale could preferentially adsorb CO_2 and desorb CH_4. Moreover, studies by KGS researchers estimate that the shale has the capacity to store more than 27.6 billion tons of CO_2. The concept of storage in a tight shale is still theoretical, however, and it is probably better to consider the use of CO_2 for enhanced gas recovery (significantly lower volumes) rather than for permanent large-scale storage at this time.

Another unit for which storage capacity has not been quantified is the Knox Dolomite. The lower part of the Knox has been used for industrial-scale waste disposal in Kentucky. Two wells at the DuPont plant in Jefferson County (currently plugged) and the IMCO recycling well in Butler County (active) used porosity zones in the lower Knox as storage reservoirs. For this report, known reservoirs in the Knox were investigated to illustrate the types of reservoirs that might be possible. The Kentucky Consortium for Carbon Storage drilled a well in 2009 in Hancock County and tested the Knox to demonstrate its feasibility as a carbon storage reservoir.

Chapter 5, "Site Bank Assessment Geologic Data Report, Round 2, 2008," evaluates results from 23 specific sites for geologic carbon storage potential. Recognizing the importance of the coal industry, the Commonwealth of Kentucky identified locations appropriate for deployment of next-generation coal-based industries that would include possibilities for sequestering carbon emissions. Nominations were requested for potential locations suitable for development of coal-to-liquids or integrated gasification combined-cycle electricity-generation utilities. Nineteen original sites were proposed and assessed in October 2007. In December 2007, an additional 26 sites were nominated for evaluation and included in a "site bank." A total of 23 sites were evaluated by the Kentucky Geological Survey to provide geologic criteria related to carbon storage potential (three were not evaluated because of lack of location data). This assessment was incorporated along with infrastructure, environmental, and demographic data into an overall site assessment report published in June 2008.

In summary, this report was written to serve as a resource for evaluating carbon dioxide management options in Kentucky. From potential economic benefit in enhanced oil and gas recovery, to permanent deep saline storage, the commonwealth has a variety of possible options for geologic disposal of CO_2. Further demonstrations and pilot projects are necessary to fully characterize this potential, and to reduce the risks of implementing a commercial CO_2 storage field.

Chapter 1: Introduction and Background Material

Stephen F. Greb and David C. Harris

Strategies to mitigate man-made input of carbon dioxide into the atmosphere will involve a portfolio of strategies, such as fuel switching, energy conservation, and terrestrial sequestration (tillage practices, tree planting, wetlands reestablishment, etc.). Because fossil fuels will continue to be the principal source of energy in the near-term, mitigating the input of CO_2 into the atmosphere resulting from fossil-fuel usage is critical. The U.S. Department of Energy has determined that one of the most promising mitigation technologies is geologic carbon sequestration (U.S. Department of Energy, 1999, 2004). Geologic sequestration injects captured carbon dioxide into subsurface rock reservoirs deep beneath the earth's surface.

Data on the potential for geologic carbon storage in Kentucky and surrounding areas have been gathered by the Kentucky Geological Survey as part of a series of research projects in cooperation with DOE. In 2000, Kentucky joined four other states in establishing the Midcontinent Interactive Digital Carbon Atlas and Relational Database (MIDCARB), which was initially a 2-year compilation of data on carbon emissions and potential sinks, housed on data servers, and accessed through a common Web portal (www.midcarb.org). MIDCARB was subsequently expanded to be included in a collection of regionally managed databases called NatCarb, which contains information on CO_2 storage options and storage potential nationwide (www.natcarb.org). Next, KGS participated in two partnership projects, the Midwest Geological Sequestration Consortium and the Midwest Regional Carbon Sequestration Partnership, both part of the DOE Regional Carbon Sequestration Program. Phase I (2001–05) of the partnerships concentrated on regional assessments of potential geologic reservoirs (sinks) and seals, and determined potential sites for future small-scale demonstration projects. Work by the Midwest Geological Sequestration Consortium focused on the Illinois Basin, which includes much of western Kentucky (Frailey and others, 2005), whereas work by the Midwest Regional Carbon Sequestration Partnership focused on the eastern Midcontinent and northern Appalachians, including central and eastern Kentucky (Wickstrom and others, 2005).

Research in phase II (2005–09) of the regional partnerships is focused on implementing small-scale (thousands of tons) CO_2 injection demonstrations; monitoring, verifying, and accounting of injected CO_2 in the demonstrations; and more detailed geologic characterization of the sinks and seals identified in phase I. One of the Midwest Regional Carbon Sequestration Partnership demonstrations is scheduled at Duke's East Bend power station in Boone County, Ky., in the summer of 2009. KGS also joined the Southeast Regional Carbon Sequestration Partnership during phase II to assess coals for sequestration and enhanced coalbed methane in the Black Warrior Basin of Alabama and the central Appalachian Basin of southwestern Virginia and southeastern Kentucky. Funding for the phase II projects was matched by grants from the Kentucky Energy and Environment Cabinet (previously the Governor's Office of Energy Policy).

The level of State-sponsored funding for KGS carbon-sequestration research dramatically increased in the summer of 2007, when the Kentucky Legislature passed House Bill 1 in a special session. HB 1 authorized $5 million for research by KGS in the areas of CO_2-enhanced oil recovery, CO_2-enhanced gas recovery, and permanent geologic sequestration of CO_2. More specifically, HB 1 required drilling research wells in Kentucky's eastern and western coal fields to assess the suitability of subsurface reservoirs for CO_2 storage, and evaluating the Devonian black shale, Kentucky's most prolific gas reservoir, for enhanced gas recovery using CO_2. HB 1 encouraged KGS to collaborate with and develop cost-sharing industry partners, who will be the beneficiaries of this important research. The collaboration led to the formation of the Kentucky Consortium for Carbon Storage (www.kyccs.org), which has ongoing research in several Kentucky counties; drilling was recently completed for a deep test hole for a carbon storage test in saline aquifers in Hancock County.

Background on Geologic Carbon Storage Characteristics of CO_2 Relative to Geologic Storage

In order to better understand the potential for geologic storage in Kentucky, some background information is needed on the basic characteristics of CO_2 (including various depth, pressure, and temperature constraints); and the basic types of geologic storage reservoirs, which influence how and where CO_2 might be injected in Kentucky. Carbon dioxide is nontoxic and at surface temperatures and pressures it is a colorless and odorless gas. Carbon dioxide has been safely used in enhanced oil and gas recovery (see, for example, Jarrell and others, 2002; Melzer and Miller, 2007). Consequently, we have a good working knowledge of the behavior of CO_2 in the subsurface, although at generally smaller volumes than are being considered for industrial-scale carbon sequestration. As temperature and pressure increase (which happens with increasing depth beneath the surface), gaseous CO_2 becomes more liquid-like and liquid CO_2 becomes more gas-like, until the critical point is reached and the two phases cannot be distinguished. Beyond this point, the CO_2 is considered supercritical. The critical temperature (87.8°F) and pressure (1,073 psia) are important because the density of CO_2 increases significantly when critical conditions are reached. The density increase allows a unit mass of CO_2 to occupy a much smaller volume at supercritical pressure and temperature than it would at surface pressure and temperature. For example, 1 short ton of CO_2 gas at surface temperature and pressure occupies a volume of 18,000 ft^3, whereas supercritical CO_2 at a depth of 2,600 ft below the surface occupies a volume of 50 ft^3 (Wickstrom and others, 2005). It is this physical property of CO_2 that makes geologic storage such an attractive technology for large-scale CO_2 reductions in which millions of tons of CO_2 may need to be sequestered annually.

Previous work by the DOE partnerships and the Kentucky Consortium for Carbon Storage indicates that in Kentucky, CO_2 reaches critical conditions at approximately 2,500 ft below the surface (Fig. 1.1). Although a depth of 2,500 ft is a good regional estimate for supercritical conditions, variability in local pressure and temperature gradients means that determination of CO_2 phase at a given site or reservoir should be site-specific. For example, in the Illinois Basin (western Kentucky), depths of less than 2,100 ft are usually gas phase, depths of 2,100 to 2,900 ft are near supercritical (or could be either), and depths of more

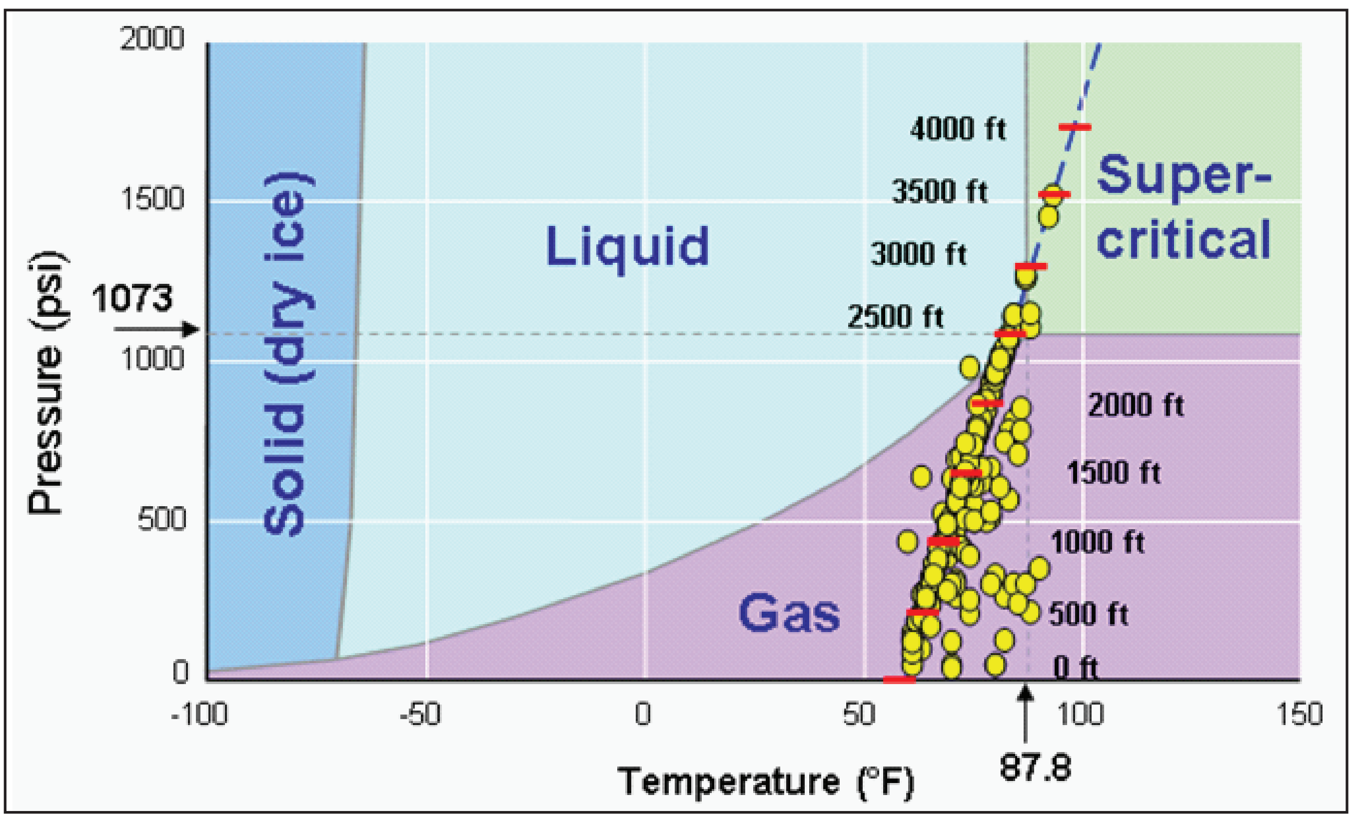

Figure 1.1. Temperature-pressure phase diagram showing fields in which solid, liquid, gas, and supercritical forms of CO_2 are stable. Data from Kentucky oil and gas wells (yellow dots) at increasing depth (red lines) plot primarily in the gas stability field (data compiled by B. Nuttall). This plot indicates that storage of dense CO_2 will require injection deeper than most oil and gas fields. Note that the supercritical phase of CO_2 is reached between 2,500 and 2,900 ft.

than 2,900 ft are considered supercritical (Frailey and others, 2005).

The pressure-temperature-depth properties of CO_2 also influence how injected CO_2 will interact with naturally occurring fluids (e.g., brine, oil) or other gases filling the pore spaces in subsurface rock units. At its supercritical phase, CO_2 should be partly miscible; that is, it should react with the fluids and gases in the pore space. In contrast, gaseous-phase CO_2 should be mostly immiscible; that is, it should largely remain as a distinct gas phase even as it displaces and interacts with other reservoir fluids and gases. In reality, even supercritical CO_2 will likely displace fluids and gases in reservoirs and migrate as a separate phase, and only part of the injected volume will actually dissolve in the pore fluids in the short term (see, for example, Johnson and others, 2004). Over longer periods, supercritical CO_2 would continue to slowly dissolve in formation brines as it migrates into pore space undersaturated with CO_2. In an unusual case in Louisville in the 1980's, a bubble of supercritical CO_2 formed deep in a Knox Dolomite reservoir, after injected waste acid dissolved a cavern in the host carbonate rock. This supercritical CO_2 was completely dissolved by pumping fresh water into the reservoir over a period of 3 yr (Clark and others, 2005). Dissolution of CO_2 in saline brines will be slower, and controlled by the solubility factors discussed below.

Another property that will influence geologic carbon storage is the solubility of CO_2 in water. CO_2 solubility tends to decrease with increasing temperature, and tends to increase as pressure increases (Fig. 1.2) (Carr and others, 2003). For lower pressures and temperatures, as are common in many Kentucky reservoirs, the increased solubility from increasing pressure should more than offset the temperature effects.

The solubility of CO_2 is also decreased by higher salinity (Fig. 1.3), which is significant since the salinity of water in rock pores generally increases with depth (Frailey and others, 2005; Wickstrom and others, 2005). Deep saline reservoirs represent the largest potential sequestration target in Kentucky and worldwide (U.S. Department of Energy, 2004, 2008a; Frailey and others, 2005; Wickstrom and others, 2005).

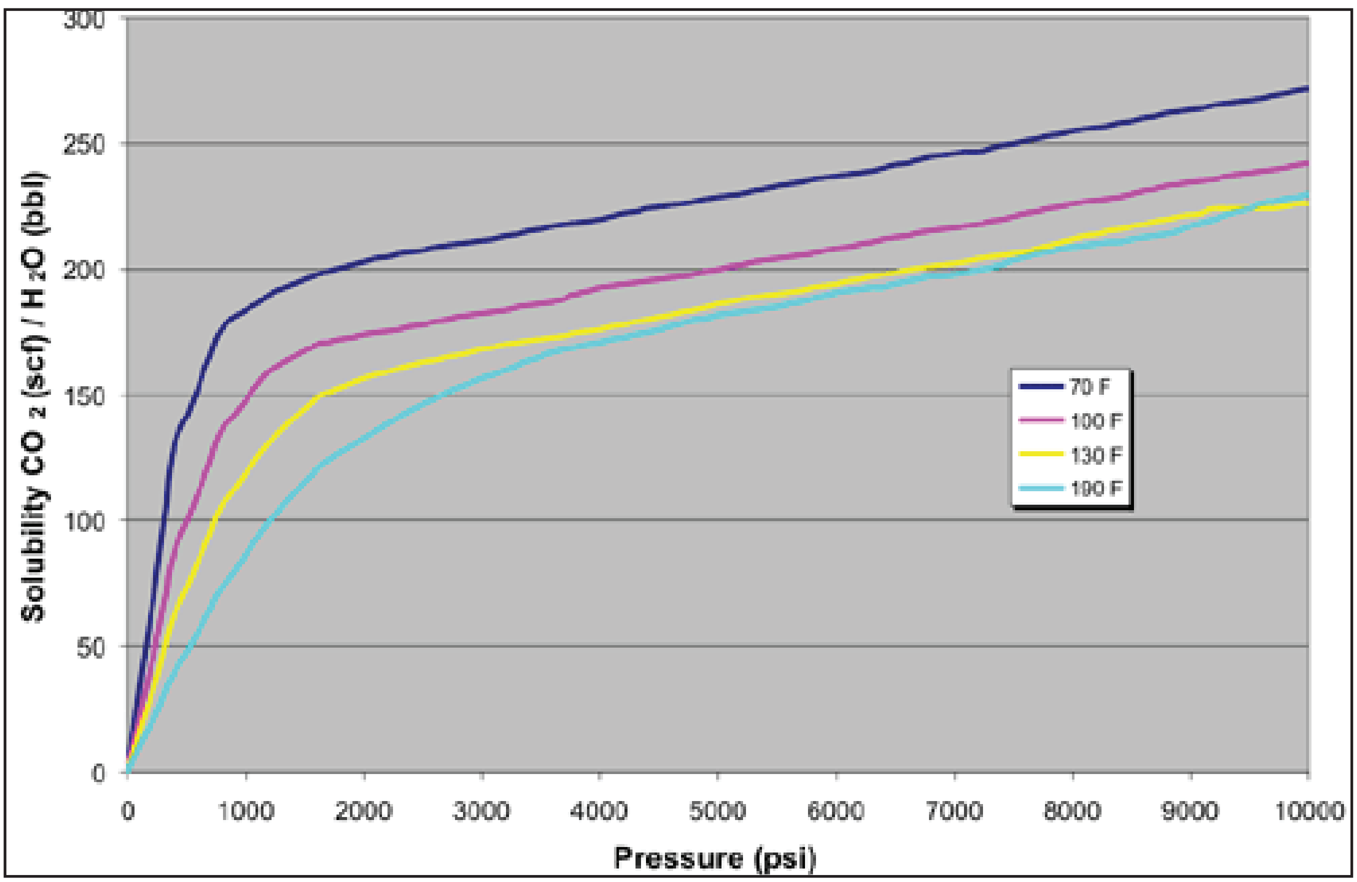

Figure 1.2. Solubility of CO_2 as a function of pressure at different temperatures (colored lines). From Carr and others (2003).

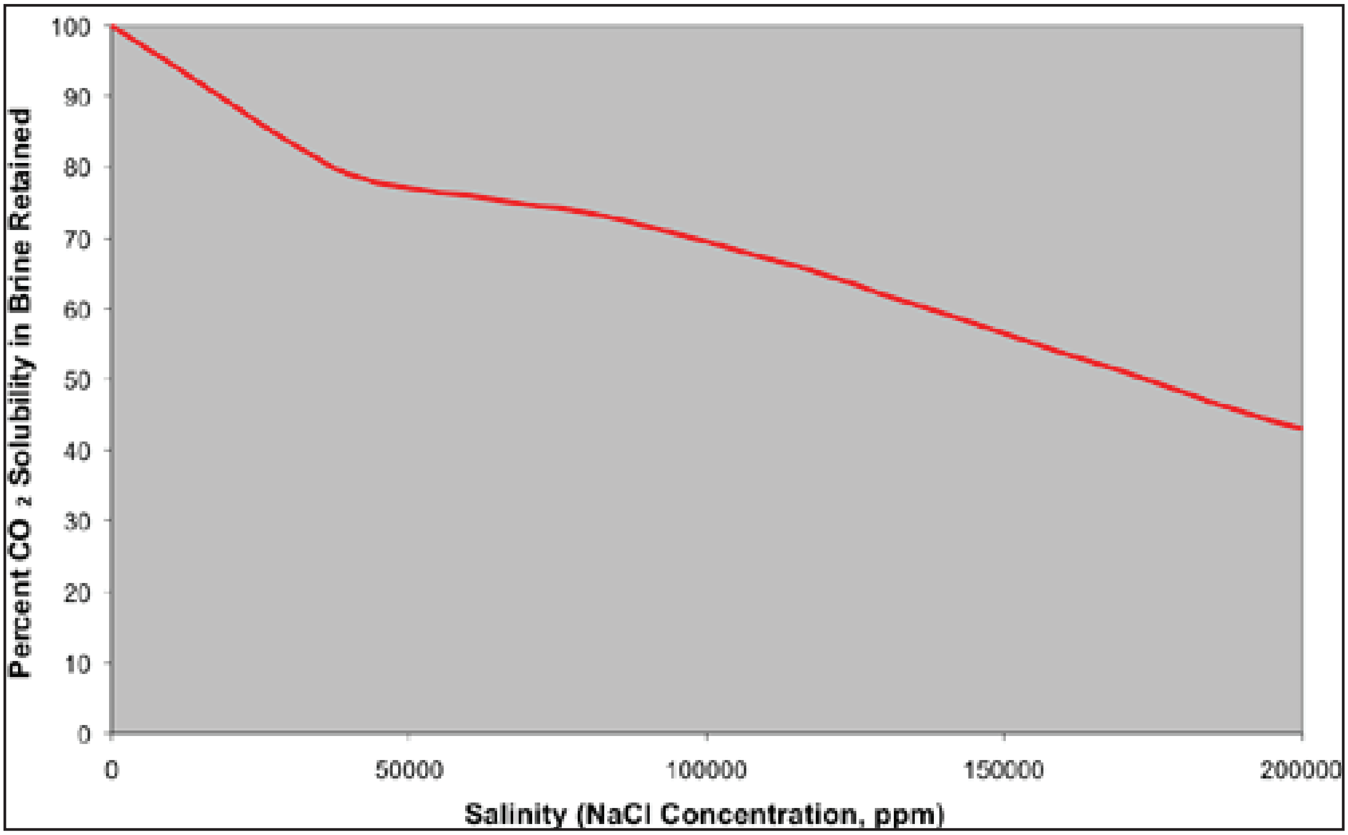

Figure 1.3. Solubility of CO_2 as a function of salinity. From Carr and others (2003).

More information about properties of CO_2 relative to carbon storage can be found at DOE's carbon sequestration Web site, www.fossil.energy.gov/programs/sequestration/, in the phase I reports of the regional partnerships (Frailey and others, 2005; Wickstrom and others, 2005), at the MIDCARB Web site (Carr and others, 2003), and at the EPA's geologic sequestration Web site, www.epa.gov/safewater/uic/wells_sequestration.html.

Types of Geologic Storage

Several broad categories of geologic reservoirs are being investigated by DOE for potential carbon storage: (1) deep saline formations, (2) depleted or abandoned oil and gas fields, (3) unmineable coal beds, (4) organic-rich shales, and (5) basalts (U.S. Department of Energy, 1999, 2004). All occur in Kentucky, although the first four have the greatest potential for carbon storage, as inferred from a relatively long history of investigation and exploitation.

Deep saline formations, also known as saline reservoirs or aquifers, are rock units that contain natural waters in the pore spaces between the mineral grains and in fractures within the rock. Also called brines, the saline waters typically have high enough salinity (greater than 10,000 ppm) that they are considered nonpotable. Some saline formations are regionally widespread; consequently, they have large potential storage volumes, which is why they are attractive targets for carbon storage. The amount of pore space in aquifers considered to have storage potential typically ranges from 5 to 20 percent of the total rock volume.

Phase I of the DOE regional partnership research determined that deep saline formations have the greatest potential for large-volume carbon storage. Hence, they are a major focus of geologic carbon storage investigations. In Kentucky, the potential total storage volumes may exceed 6.6 billion short tons (Frailey and others, 2005; Wickstrom and others, 2005). Not all of the saline aquifer capacity will be accessible, however. It is important to understand that no deep rock unit is completely homogenous or open to injection of fluids and gases. Factors such as reservoir heterogeneity, CO_2 buoyancy, sweep efficiency, and rock and water chemistry are likely to reduce the theoretical capacity to an "effective capacity" (Bachu and others, 2007). The effective capacity is then further reduced by a variety of regulatory, economic, and social issues to produce a "practical capacity."

In deep saline formations, injection would likely be done under supercritical conditions. As a dense phase, however, the pressurized CO_2 that is injected into a porous rock unit will likely displace the water within the pore space. Over a long period, the CO_2 will dissolve into the formation fluids. The amount of CO_2 that dissolves will be a function of brine-water chemistry, salinity, permeability, pressure, and temperature.

Deep saline reservoirs are only suitable for CO_2 storage if one or more overlying nonporous formations are present to serve as a vertical seal, preventing upward movement of the buoyant CO_2. Reservoirs within deep saline formations can be laterally unrestricted (regionally widespread permeability) or restricted by stratigraphic and structural barriers. Most reports of carbon storage that discuss saline aquifers assume that low fluid velocities under unconfined conditions will produce hydrodynamic trapping (Bachu and others, 2007). But as in natural gas (methane) storage fields, some degree of structural trapping may be beneficial for containment and monitoring of injected CO_2.

Confirmation of the potential for industrial-scale injection of CO_2 into saline aquifers (at least in some areas) is provided by Statoil's Sleipner Field in Norway. Approximately 1.1 million short tons of CO_2 have been injected annually into a brine-bearing sandstone at depths of approximately 3,000 ft beneath the North Sea since 1996 (Zweigel and others, 2004). The Sleipner project continues to be a focus of research on the practical aspects of large-volume injections, including post-injection chemical changes of the saline reservoir and its overlying seals (see, for example, Johnson and others, 2004), and methods for monitoring subsurface CO_2 plumes (see, for example, Chadwick and others, 2006) in deep saline rock units.

In the United States, the first DOE-sponsored experimental injection into a deep saline rock unit was the Frio project near Houston, Texas. In 2004, small amounts of CO_2 (1,764 short tons) were injected into a 70-ft-thick porosity zone in the Frio Sandstone at a depth of 5,700 ft (Hovorka and others, 2005, 2006; Kharaka and others, 2006). Data from this project continue to be collected, but the project demonstrated that CO_2 can be safely injected and the fate of the CO_2 in the subsurface successfully monitored. Additional deep saline reservoir tests are being planned around the United States as part of the DOE-sponsored regional carbon sequestration partnerships.

Several DOE-sponsored phase II demonstration tests by the Midwest Geologic Sequestration Consortium and Midwest Regional Carbon Sequestration Partnership are planned in our region. The Midwest Geologic Sequestration Consortium recently completed a test of sequestration into coal beds in central Illinois, although results have not yet been made public. The Midwest Regional Carbon Sequestration Partnership recently completed a test of sequestration into a deep saline aquifer in northern Michigan (Gupta, 2008; U.S. Department of Energy, 2008b). The Midwest Regional Carbon Sequestration Partnership completed another deep saline test in Kentucky in 2009. Approximately 1,100 short tons of CO_2 were injected into the Cambrian Mount Simon Sandstone at depths of 3,230 to 3,530 ft beneath the East Bend power station in Boone County (Midwest Regional Carbon Sequestration Partnership, 2008a; U.S. Department of Energy, 2009). As with the Frio experiment, various aspects of modeling and monitoring are continuing.

The Kentucky Consortium for Carbon Storage also drilled a deep saline test well in 2009. This test is an outgrowth of Kentucky House Bill 1 (2007) funding. The well tested the Knox Group carbonates and sandstones in Hancock County, Kentucky. Results of this project can be found at the KYCCS Web site (www.kyccs.org). Data from both of these tests will be important for understanding carbon storage potential in Kentucky.

Oil and gas fields are accumulations of hydrocarbons that have been trapped in porous rock units for millennia. Oil and gas flow through the formation to wells pumped from the surface. Because oil and gas were produced (indicating permeability), CO_2 (as a gas or liquid) should flow back into the pore space vacated by the extracted oil or gas. The mechanisms responsible for trapping the hydrocarbons should likewise trap most injected CO_2.

As demonstrated in West Texas since the early 1960's and in the Weyburn Oil Field of Saskatchewan, CO_2 can be used to enhance oil (CO_2-EOR) or gas (CO_2-EGR) recovery in depleted fields (see, for example, Plasynski and others, 2008a). In West Texas, for example, CO_2-EOR has resulted in the additional recovery of 7 to 25 percent of the original oil in place (Melzer and Miller, 2007). In this process, the CO_2 either displaces oil or gas in the reservoir (immiscible) or mixes with the oil and gas (miscible) to enhance recovery. As discussed in chapter 2, the shallow depth of most Kentucky oil fields will lead to immiscible conditions for most of our existing oil and gas fields. It is possible that revenue generated from increased production in enhanced recovery projects could be used to help offset the cost of carbon storage. Elsewhere, including the Midwest, the high cost of commercially available CO_2 has limited the use of this technology. This economic restriction is likely to change in the near future when limits are placed on carbon emissions and carbon-capture technology results in greater availability of CO_2.

In oil and gas reservoir scenarios, it is important to make the distinction between enhanced recovery using CO_2 and permanent carbon storage. In general, smaller amounts of CO_2 are needed for enhanced recovery (at least initially) because some of the injected CO_2 is produced with the oil or gas and can then be reinjected. Some of the CO_2 also remains trapped in the reservoir, where it dissolves in water or is trapped by capillary forces. The amount of CO_2 necessary to produce a barrel of oil is called the "utilization factor." Integrated over the life of EOR projects in West Texas, the net utilization factor—measured in thousand cubic feet of CO_2 per barrel of oil—equals 5 to 6 (Melzer, 2005). As with saline aquifers, the effective capacities of an oil or gas reservoir to store CO_2 will be less than the theoretical capacity. Moreover, as less oil is produced and a field becomes uneconomic for EOR, it is anticipated that many fields will transition into strictly carbon sequestration projects if there are economic benefits for CO_2 mitigation.

Unmineable coal beds are another possibility for carbon storage, with potential benefits for enhanced coalbed-methane recovery (ECBM) (Gale and Freund, 2001; Schroeder and others, 2001; Reeves, 2003). The storage process is fundamentally different from that in oil and gas fields or in saline aquifers because rather than displacing fluids in pore spaces, CO_2 adsorbs (sticks) onto the surfaces of organic matter in the coal bed. One attractive feature of the adsorption mechanism in coal is that CO_2 has a greater affinity for organic matter in the coal matrix than does methane (CH_4). Thus, injected CO_2 should preferentially displace methane, thereby enhancing CH_4 production. Ratios of 3:1 to 6:1 have been determined for CO_2-to-CH_4 displacement in some Illinois coals (Frailey and others, 2005). Like EOR or EGR, ECBM with CO_2 will be more feasible when lower-cost CO_2 becomes available, helping to offset the cost of carbon capture. Kentucky currently has no economic coalbed-methane production, so injection of CO_2 into coal beds would be strictly for long-term storage.

The adsorption mechanism also means that CO_2 injection into coals would not necessarily have to be at supercritical depths for storage or ECBM. Storage would have to be at depths below the level of surface fracturing to prevent leakage of injected CO_2. Beyond that, the depth of coals used for injection would be more related to their mineability. If CO_2 is injected into a coal for permanent storage, then the coal ideally would never be mined, since mining would release the injected CO_2. For this reason, DOE has used the term "unmineable coals" when describing this carbon-storage option. Although there is no single definition of "unmineable," various DOE-sponsored partnerships have inferred that coals more than 1,000 ft deep (below lowest drainage) would be considered uneconomic to mine with foreseeable technology and might be considered for carbon storage (Frailey and others, 2005; Wickstrom and others, 2005). In the Illinois Basin, the Midwest Geologic Sequestration Consortium considered coals at 300 to 500 ft depth as potentially suitable for ECBM; coals at 500 to 1,000 ft as suitable for permanent carbon storage if thin (1.5 to 3.5 ft thick—but thicker coals would be potentially mineable); and coals at 1,000 ft or more depth as unmineable regardless of thickness, and suitable for either permanent storage or ECBM (Frailey and others, 2005). The Southeast Regional Carbon Sequestration Partnership, which KGS joined during phase II, also used a depth of 1,000 ft or more as unmineable.

Field and laboratory studies show, however, that carbon storage in coal beds faces a number of technical challenges. Laboratory experiments on coal core and crushed coal, for example, have indicated that (1) there are variable limits to the amount that CO_2 may enhance CH_4 recovery, (2) at low pressures, CH_4 may actually readsorb into the coal matrix during CO_2 injection, and (3) CO_2 adsorption causes swelling of the coal matrix, which lowers the coal bed's permeability, and therefore limits the amount of CO_2 that can be injected or stored (Levine, 1996; Frailey and others, 2005). There has been limited testing of the effects of swelling on injection in the field, although a pilot test of CO_2 injection for enhanced coalbed methane recovery in the Burlington Resources Allison unit, San Juan Basin, in New Mexico documented large decreases in coal permeability in CO_2 injection wells (Pekot and Reeves, 2002, 2003).

Multiple demonstration tests are planned in surrounding states in the near future that should provide data on the viability of CO_2 injection into coals for storage and ECBM. This is important because differences in coal rank, chemistry, cleating, and other factors may influence coal swelling and adsorption. A well in the Springfield coal (W. Ky. No. 9) in central Illinois has been drilled and sampled as part of phase II Midwest Geologic Sequestration Consortium research (Illinois State Geological Survey, 2007; U.S. DOE Fossil Energy Techline, 2008), and test injection of CO_2 into coal occurred in the summer-fall of 2008. During this test, 111 short tons of CO_2 were injected intermittently over 200 days. Injection rates fell during the test from an initial 2.2 short tons/day to a final 0.66 short ton/day, presumably because of permeability reduction caused by swelling of the coal (D. Morse, Illinois State Geological Survey, personal communication, 2009). Elsewhere, Southeast Regional Carbon Sequestration Partnership has planned CO_2 injection tests in Alabama and southwestern Virginia (Pashin and others, 2004; Pashin and Clark, 2006; Ripepi and others, 2008). The Virginia test has been initiated, but results are not yet public. In addition, KGS, as part of the Southeast Regional Carbon Sequestration Partnership, has planned a laboratory investigation of coal swelling in eastern Kentucky coals.

An overview of the factors that influence carbon storage and use of CO_2 for enhanced methane recovery can be found in the phase I reports of the Midwest Geologic Sequestration Consortium (Frailey and others, 2005) and the Southeast Regional Carbon Sequestration Partnership project (Pashin and others, 2004). Maps of CO_2 storage and ECBM recovery possibilities for coals in the Carbondale Formation in Kentucky (and the rest of the Illinois Basin) are shown in the phase I final report of the Midwest Geologic Sequestration Consortium (Frailey and others, 2005, p. 150–153). In Kentucky, the areas are mostly limited to a narrow belt south of the Rough Creek Fault System in the Rough Creek Graben, where coals are preserved at greater depths. Likewise, a map of the general area in which coal beds of eastern Kentucky are deep enough to be considered for ECBM or carbon storage is shown in the phase I final report of the Midwest Regional Carbon Sequestration Partnership (Wickstrom and others, 2005). This area is restricted to the southern part of the Eastern Kentucky Syncline and the Middlesboro Syncline.

Organic-rich shales are a fourth possibility for geologic carbon storage in Kentucky. The Devonian black shales of Kentucky are the state's most prolific natural gas (CH_4) producer. Like coal beds, the shales have high total organic content and low matrix porosity. The reservoir similarity suggests that the adsorption mechanisms described for coals should also occur in black shales, although to a lesser degree because of the lower organic content. Likewise, injection of CO_2 into the shales should displace naturally occurring CH_4 in the shale matrix and along fractures in the shale, so that enhanced gas recovery is possible. This would allow a revenue stream to be developed to help offset the costs of carbon storage, as with carbon storage and EOR, EGR, and ECBM.

KGS (through DOE and State of Kentucky funding) is a national leader in researching the potential for carbon storage in subsurface shales (Nuttall and others, 2005). The potential of this type of reservoir is great, but remains speculative. Aside from issues discussed for injection of CO_2 in coal beds, the extremely low permeabilities of the shales (normally considered a seal or confining interval) may limit the rate at which CO_2 can be injected. The widespread distribution and thickness of the Devonian black shales in the subsurface means that they could be a very important storage option in Kentucky, however, with potential CO_2 storage capacities of more than 27.6 billion short tons (Nuttall and others, 2005; Wickstrom and others, 2005). Kentucky's House Bill 1 (2007) specifically requires applying CO_2 enhanced gas recovery technology to the Devonian black shale. For updates on this project, see the KYCCS Web site (www.kyccs.org).

Basalts are the last of the potential reservoirs that have been identified as having potential for geologic carbon storage. Basalt is an igneous rock formed from lava. Rather than by miscible, immiscible, or adsorption mechanisms, carbon could be stored in basalts through chemical trapping mechanisms. Chemical trapping, also called mineral trapping, occurs when injected CO_2 reacts with minerals and elements in the basalt to form carbonate minerals. Because the injected CO_2 is altered to a relatively stable and solid phase, CO_2 would be permanently stored (Seifritz, 1990; Goldberg and others, 2008). The injectivity of the basalt, kinetics of the reactions, and potential for precipitation of minerals and scaling at the point of injection are some of the issues that need to be evaluated before this type of mechanism can be utilized for large-scale storage. A small-scale carbon-storage demonstration test in thick basalts is planned by the Big Sky Regional Partnership as part of their phase II research, which will help answer some of the above questions (Plasynski and others, 2008b).

In Kentucky, basalts are not widespread, and are encountered in association with the Precambrian Middle Run Formation. Basalt has been encountered in only two wells, and detailed petrographic and geochemical data are available for these intervals (Walker, 1991). Petrographic analysis of these basalts indicates they have been highly altered, both by a mild metamorphism and by surface weathering (Walker, 1991). The resulting mineralogic changes may affect how these basalts react with injected CO_2. These limitations, as well as the potential limitations to injection rates and sequestration volumes, will probably eliminate basalts as an option in Kentucky at this time.

Subsurface Area Required for Carbon Storage

One of the most important issues concerning geologic carbon sequestration is the large volume of CO_2 that will likely need to be sequestered. A 500-MW, bituminous-coal-fired power plant produces 2.2 to 4.4 million short tons of CO_2/yr. How much of that CO_2 will be required to be stored remains uncertain, but the FutureGen initiative based its proposals on annual storage volumes of 1.1 million short tons.

The area that will be required to store an industrial-scale volume of 1.1 million short tons of CO_2 (1 million metric tons) was calculated, based on some model criteria, for a Kentucky deep injection well. Table 1.1 shows the calculated areas of an injected CO_2 plume of 1.1 million short tons at different thicknesses and porosities of reservoir rock, using the MidCarb solubil-

Table 1.1. Calculations for a model western Kentucky CO_2 injection well to illustrate range of surface injection areas required using the MidCarb (2003) saline storage calculator (www.kgs.ku.edu/Magellan/Midcarb/aquifer.html).

Reservoir Thickness	*Porosity*	*Area Needed for 1.1 Million Short Tons of CO_2*	
(ft)	*(percent)*	*(acres)*	*(mi²)*
5	5	106,225	165.92
	10	53,112	82.96
	15	35,408	55.31
	20	26,556	41.48
10	5	53,112	82.96
	10	26,556	41.48
	15	17,704	27.65
	20	13,278	20.74
20	5	26,556	41.48
	10	13,278	20.74
	15	8,852	13.83
	20	6,639	10.37
50	5	10,622	16.59
	10	5,311	8.30
	15	3,541	5.53
	20	2,656	4.15
100	5	5,311	8.30
	10	2,656	4.15
	15	1,770	2.76
	20	1,328	2.07

ity of CO_2 and volumetrics calculator for a saline reservoir (MidCarb, 2003). The calculation is based on a western Kentucky reservoir at 4,000 ft depth, a temperature of 90°F, a pressure of 1,700 psi, and a salinity of 170,000 ppm. Differences in temperature, pressure, salinity, rock heterogeneity, actual permeability, and other factors could also influence area estimates. Obviously, the best reservoirs would be 100 ft or more in thickness with porosities of 20 percent or more. Unfortunately, most known oil and gas and saline reservoirs in Kentucky are less than 20 ft thick, with average porosities of less than 15 percent. Only the Mount Simon Sandstone and Rome Formation have porosities of more than 10 percent in intervals more than 100 ft thick.

Contents of This Report

This report documents the results of a multifaceted regional evaluation of carbon storage potential in Kentucky funded by the Energy and Environment Cabinet (formerly the Governor's Office of Energy Policy). Four separate tasks were defined as part of this project, each of which contributes to the goal of implementing future geologic sequestration projects in the state. The individual tasks range from regional stratigraphic summaries to site-specific evaluations. Significant new data have resulted from this work, including reservoir parameters important for CO_2-enhanced oil recovery and chemical constituents of subsurface brines.

Task 1 evaluated and characterized major oil fields in Kentucky for their suitability in CO_2-enhanced oil recovery techniques. Oil fields were evaluated for EOR suitability using KGS reservoir data. Results of this work are presented in chapter 2.

Task 2, as originally proposed, involved sampling and chemical analysis of subsurface formation waters (brines) in two oil fields being considered for CO_2-EOR. Soon after this work began, a wealth of brine geochemistry data from across the state was located at KGS. These older data, in paper format, had never been entered into a computer database to allow analysis of regional or depth-related trends. These 356 analyses from wells in 23 counties across the state were determined to be of more value than new brine data collected from only two sites. Chapter 3 presents the results of this effort, and provides a valuable new data set for use in modeling the geochemical effects of CO_2 injection.

Task 3 evaluated the geology of the commonwealth to identify areas and geologic formations best suited for CO_2 storage. This study continued an appraisal started as part of Kentucky's effort to prepare a proposal for the Department of Energy FutureGen project (www.futuregenalliance.org). This work has focused on the major river corridors in the state, because there are existing coal-burning power plants in these areas, which will also be the likely sites of new gasification facilities. A new series of cross sections paralleling the river corridors is an important contribution, and is discussed in chapter 4.

Task 4 was more site-specific, and has provided preliminary CO_2 storage evaluations of sites nominated for coal gasification projects in the Kentucky site bank program (www.energy.ky.gov/efsb.htm). These CO_2 evaluations were included as part of the overall site rankings published by the Energy and Environment Cabinet, and are also included in chapter 5 of this report.

Appendix A of this report includes a discussion on the various types of geologic data required to evaluate the CO_2 storage potential of a site. The appendix also includes a new map of commercial reflection seismic data coverage for Kentucky. Seismic data are important for geologic characterization of an area prior to injection, and this map identifies the locations of seismic lines that are available for purchase at lower cost than acquiring new data.

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Chapter 2: Assessment of Kentucky Fields for CO_2-Enhanced Oil Recovery

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Introduction

Enhanced oil recovery (EOR) using carbon dioxide (CO_2) has been successful in the United States, where the technology is recovering approximately 300,000 barrels of oil per day beyond that produced during the primary and secondary phases of field production (U.S. Department of Energy, no date a). The additional oil produced represents about 4 percent of the original oil in place nationwide and 10 to 15 percent of the original oil in place in the Permian Basin of Texas (Melzer and Miller, 2007). More recently, EOR has been viewed as a mechanism to sequester (i.e., store) some of the CO_2 used in the EOR process, thereby defraying part of the sequestration costs (Melzer and Miller, 2007; U.S. Department of Energy, 1999). Though still conceptual, over time an EOR project would be envisioned to transform into a strictly sequestration project in which sequestration costs were covered, for example, by carbon credits (U.S. Department of Energy, 1999).

In contrast to its more than 40 year history in the United States, the history of CO_2-EOR in Kentucky and surrounding regions in the Appalachian and Illinois Basins has been very limited, with only a handful of small projects implemented (see, for example, Duchscherer, 1965; Miller, 1990; Bardon and others, 1991; Miller and others, 1994; Miller and Hamilton-Smith, 1998). Remaining oil in place in Kentucky is an estimated 1.7 billion barrels, which represents 71 percent of the estimated 2.4 billion barrels of original oil in place (B.C. Nuttall, Kentucky Geological Survey, 2005, unpublished data). The proportion of remaining oil that could be recovered using CO_2-EOR is speculative because of the paucity of CO_2-EOR precedents in the region, but assuming that proportion equals 6 to 7 percent — a somewhat conservative estimate based on likely reservoir conditions in Kentucky — then 700,000 additional barrels of oil could be recovered.

Nationwide, EOR in the context of sequestration is still a very immature field; therefore, there are no historic projects that could serve as guides. Nevertheless, conventional EOR experience is providing guidelines that will allow screening of possible CO_2-sequestration projects (see, for example, Kovscek, 2002; Carr and others, 2008). What these studies suggest is that reservoir and oil properties, and surface facilities will likely exert strong influences on the efficacy and economic viability of CO_2-EOR projects within the context of sequestration.

Prior to this analysis, only a few studies have systematically examined the EOR potential in Kentucky. The Tertiary Oil Recovery Information System (TORIS) was commissioned by the U.S. Department of Energy in the 1980's to study EOR potential nationwide, including Kentucky (U.S. Department of Energy, no date b). The TORIS database system provided a compilation of geologic and engineering parameters needed to evaluate potential oil recovery. Today, the updated TORIS database provides critical reservoir data for 46 reservoirs in 33 fields in Kentucky, and it provides the basis for much of EOR analysis in this study (Nuttall, 2000). More recently, Advanced Resources International conducted EOR studies in the Appalachian Basin, where they found that 68 reservoirs were suitable for EOR, with a potential yield of 1.2 billion barrels of oil (Petroleum Technology Transfer Council, 2005).

The dearth of systematic reservoir studies focusing on EOR and actual CO_2-EOR projects in Kentucky provides the motivation for this study, in which the overarching goal is to provide a semiquantitative assessment of CO_2-EOR potential. More specifically, this study uses reservoir screening criteria described by Kovscek (2002) and Carr and others (2008) to develop an inventory and ranking of 70 oil reservoirs in 51 fields that may have favorable characteristics for CO_2-EOR. The ranking provides a high-level framework for conducting more detailed reservoir and modeling studies on selected reservoirs that can be used to predict performance during CO_2-EOR. An uncertain CO_2 supply is a significant hurdle for EOR projects in the region; therefore, the volume of CO_2 used in EOR and the volume of sequestered CO_2 are estimated. The estimated volumes will provide a basis for estimating CO_2 costs, which will be a significant part of total project costs, especially during the early period of implementation.

Methods

The 51 analyzed fields from 25 counties in eastern, central, and western Kentucky (Fig. 2.1, Table 2.1) are a small proportion of the more than 1,500 oil and gas fields that are formally recognized in Kentucky (Kentucky Division of Oil and Gas Conservation, 2008). The analyzed fields include 71 reservoirs that

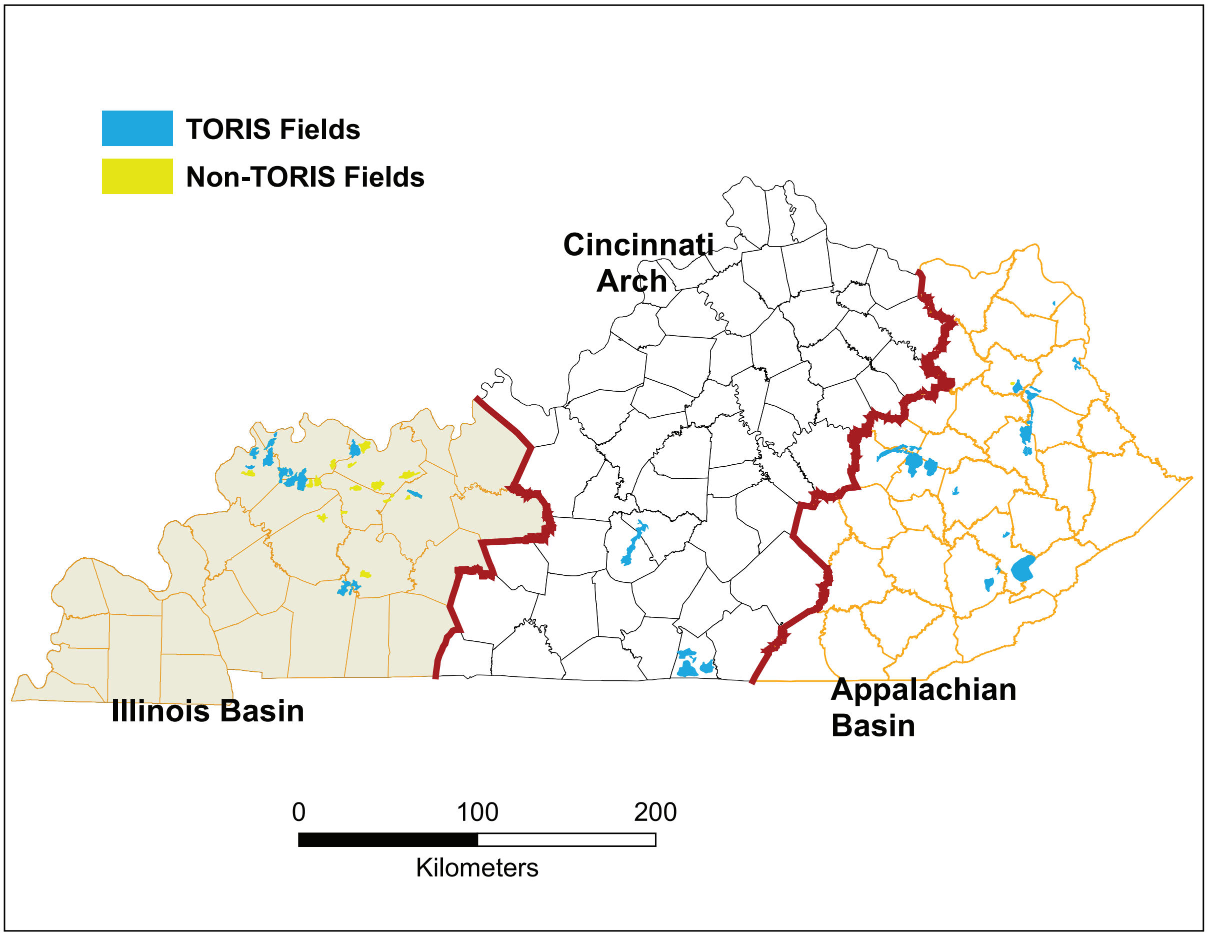

Figure 2.1. Fields evaluated for CO_2-EOR potential include those from the TORIS database (N = 33, blue areas) and non-TORIS fields (n = 18, yellow areas) having requisite characteristics discussed in the "Introduction."

range in age from Ordovician to Pennsylvanian, the majority (77 percent) of which are Mississippian (Fig. 2.2). The reservoirs include a variety of clastic (70 percent) and carbonate (30 percent) reservoirs.

TORIS data used for reservoir analysis and as inputs for screening criteria are reported by field and geologic play. Fields are administrative groupings of oil or gas wells that produce from the same or multiple (stacked) reservoirs. For example, the Dixie/Dixie West Field produces oil from the Chester, Waltersburg, and Tradewater reservoirs (see entries 11a–c, Table 2.1). Results of this study are provided primarily by field designation. The term "reservoir" refers to the body of rock — including rock matrix and pore space — that contains oil, gas, or water (or all three) in a field. It is the most fundamental subsurface volume of interest when addressing the extraction of oil and gas. Geologic plays are accumulations of oil or gas that share nearly identical characteristics of stratigraphy, reservoir type, trapping style, and seal type (Houseknecht, 1997). Oil and gas accumulations defined as plays are therefore often distributed across large areas within a sedimentary basin, and may encompass numerous fields.

To further broaden the assessment, we examined 18 fields in addition to the 33 TORIS fields. These fields, called "non-TORIS fields," have one or more of the following characteristics: (1) previously waterflooded, (2) large surface footprint, possibly indicating high potential for larger volumes of unrecovered oil, (3) large estimated original oil in place, or (4) at least four productive or previously productive wells. A waterflood is a secondary oil recovery method in which water is injected into a reservoir to displace additional oil toward producing wells.

Reservoir parameters in the TORIS database come from a variety of sources, including open-hole wireline logs, core analyses, and oil samples. These data sources are often sparse and outdated and consequently might

Table 2.1. Fields and reservoirs analyzed in this study. Based on this analysis, fields that rank in the upper quartile (n = 18) are highlighted in bold. Field ID designations are used to identify fields in subsequent tables.

ID	*Field Name*	*County*	*Reservoir*	*Discovery Date*	*Depth (ft)*	*Temperature (°F)*
TORIS fields						
1	Albany North	Clinton	Knox	1961	1,800	72
2a	Apex/Hardeson/Dukes Ridge CONS	Christian/ Muhlenberg	Ste. Genevieve	1954	715	76
2b	Apex/Hardeson/Dukes Ridge CONS	Christian/ Muhlenberg	Corniferous	1954	934	70
3	Ashley	Powell/Wolfe	Corniferous	1917	910	71
4	Big Sinking	Lee/Estill/Powell/ Wolfe	Corniferous	1918	1,036	70
5a	Birk City	Daviess/Henderson	Chester	1938	1,497	82
5b	Birk City	Daviess/Henderson	Ste. Genevieve	1938	1,860	84
6	**Bulan CONS**	**Perry**	**Big Lime**	**1960**	**2,350**	**76**
7	**Bull Creek CONS**	**Perry/Letcher**	**Big Lime**	**1965**	**3,030**	**88**
8	Concord CONS	Clinton	Knox	1941	1,800	74
9	Cutshin DBS	Leslie	Big Lime	1979	3,200	86
10	Daley DBS	Leslie/Perry	Big Lime	1970	3,136	87
11a	Dixie/Dixie West	Henderson/Union/ Webster	Chester	1945	2,277	86
11b	Dixie/Dixie West	Henderson/Union/ Webster	Tradewater	1945	977	76
11c	Dixie/Dixie West	Henderson/Union/ Webster	Waltersburg	1945	1,778	78
12	Elna	Johnson	Weir	1921	750	68
13	Fallsburg CONS	Lawrence	Berea	1912	1,750	73
14	Greensburg	Green/Taylor	Laurel	1955	442	79
15	Highland	Breathitt	Corniferous	1954	1,900	80
16a	**Hitesville CONS**	**Union/Henderson**	**Aux Vases & Waltersburg**	**1954**	**2,566**	**86**
16b	Hitesville CONS	Union/Henderson	Chester	1954	2,058	85
16c	Hitesville CONS	Union/Henderson	Ste. Genevieve	1954	2,592	88
17	Ida CONS	Clinton	Knox	1959	1,750	73
18	Irvine-Furnace CONS	Estill/Powell	Corniferous	1947	800	69
19	Isonville CONS	Elliott	Weir	1917	1,010	75
20	Ivyton	Magoffin	Weir	1919	1,215	80
21	Keaton-Mazie CONS	Lawrence/Johnson	Weir	1920	850	74
22	Lee Chapel	Clinton	Knox	1975	1,577	74
23	Martha	Lawrence	Weir	1922	900	70
24	Mine Fork	Johnson	Weir	1919	800	68
25a	**Morganfield CONS**	**Union**	**Caseyville**	**1943**	**1,406**	**84**
25b	**Morganfield CONS**	**Union**	**Chester**	**1943**	**2,145**	**91**

Table 2.1. Fields and reservoirs analyzed in this study. Based on this analysis, fields that rank in the upper quartile (n = 18) are highlighted in bold. Field ID designations are used to identify fields in subsequent tables.

ID	*Field Name*	*County*	*Reservoir*	*Discovery Date*	*Depth (ft)*	*Temperature (°F)*
25c	Morganfield CONS	Union	Ste. Genevieve	1943	2,616	88
25d	Morganfield CONS	Union	Waltersburg	1943	1,833	88
26	Naples	Muhlenberg	Berea	1968	1,000	71
27	Oil Springs CONS	Magoffin/Johnson	Weir	1919	1,100	80
28	Petty Knob	Clinton	Knox	1980	1,750	73
29a	Poole CONS	Webster/Henderson	Aux Vases & Waltersburg	1943	1,775	86
29b	Poole CONS	Webster/Henderson	Chester	1943	2,030	83
29c	Poole CONS	Webster/Henderson	Ste. Genevieve	1943	2,560	91
30a	**Smith Mills/Smith Mills North CONS**	**Henderson/Union**	**Chester**	**1942**	**2,341**	**85**
30b	Smith Mills/Smith Mills North CONS	Henderson/Union	Ste. Genevieve	1942	2,635	88
31	Taffy CONS	Ohio	Chester	1926	625	72
32a	**Uniontown CONS**	**Union**	**Aux Vases & Waltersburg**	**1942**	**1,784**	**80**
32b	Uniontown CONS	Union	Chester	1942	2,237	83
33	Walker Creek CONS (Big Andy)	Lee/Wolfe	Corniferous		1,275	80
Non-TORIS fields						
34	Barnett Creek CONS	Ohio	Tar Springs	1929	650	74
35a	Barrett Hill CONS	McLean/Ohio	Bethel	1929	1,161	67
35b	**Barrett Hill CONS**	**McLean/Ohio**	**Tar Springs**	**1929**	**975**	**64**
36	Bells Ferry CONS	McLean	Jackson	1952	2,340	83
37a	**Cane Run CONS**	**Daviess**	**Hardinsburg**	**1938**	**860**	**70**
37b	**Cane Run CONS**	**Daviess**	**Tar Springs**	**1938**	**778**	**64**
38	Curdsville CONS	Daviess	Palestine	1944	1,390	72
39	**Euterpe North CONS**	**Henderson**	**Hardinsburg**	**1948**	**1,735**	**74**
40	Fannin CONS	Elliott	Berea	1950	1,080	78
41a	Griffith CONS	Daviess	Jackson	1946	1,494	70
41b	Griffith CONS	Daviess	Palestine	1946	1,000	69
42a	**Guffie CONS**	**McLean**	**Big Clifty**	**1946**	**1,908**	**69**
42b	**Guffie CONS**	**McLean**	**Tar Springs**	**1946**	**1,706**	**65**
43a	Hanson CONS	Hopkins	Cypress	1962	2,385	62
43b	**Hanson CONS**	**Hopkins**	**Tar Springs**	**1962**	**2,408**	**65**
44	Hardeson CONS	Muhlenberg/ Christian	Bethel	1955	884	63
45	**Maxwell CONS**	**Ohio/McLean/ Daviess**	**Tar Springs**	**1943**	**1,860**	**67**
46	**Morganfield South CONS**	**Union**	**Hardinsburg**	**1948**	**1,930**	**79**

Table 2.1. Fields and reservoirs analyzed in this study. Based on this analysis, fields that rank in the upper quartile (n = 18) are highlighted in bold. Field ID designations are used to identify fields in subsequent tables.

ID	*Field Name*	*County*	*Reservoir*	*Discovery Date*	*Depth (ft)*	*Temperature (°F)*
47	**Pratt CONS**	**Webster**	**Tar Springs**	**1943**	**1,860**	**67**
48	Rhodes School CONS	Muhlenberg	Jackson	1952	1,359	74
49	Sebree CONS	Webster/Henderson	Tar Springs	1904	1,800	73
50	Taffy CONS	Ohio	Tar Springs	1926	620	61
51a	Utica CONS	Daviess	Cypress	1927	1,450	67
51b	Utica CONS	Daviess	Tar Springs	1927	1,200	66

not provide the desired accuracy for modern reservoir analysis. Many of the reported reservoir parameters therefore represent average values for an entire field or play and do not address potential reservoir heterogeneity, which would have to be addressed in any subsequent detailed analyses. For the non-TORIS fields, reservoir parameters were calculated or extrapolated from TORIS, based on similarity where required.

Minimum miscibility pressure (MMP) is one of the most critical parameters used to assess CO_2 interactions with oil in the reservoir and hence the effectiveness of CO_2-EOR projects. The MMP is the minimum pressure at which CO_2 will mix with oil in a reservoir to form a single fluid phase. Miscibility contributes to optimal recovery of oil. Values for MMP may be determined experimentally using slim-tube tests (Jarrell and others, 2002), or, as in the case of this study, with empirical correlations. Specifically, we used the Cronquist correlation (Bank and others, 2007), which equals:

$$MMP = 15.988 * Temperature^{(0.744206+0.0011038*MW\ C5+)}$$

where: $MW\ C5+ = 4247.98641 * API^{(-0.87022)}$ and API is the API gravity of the oil. "MW C5+" is the molecular weight of hydrocarbons containing at least five carbon atoms in a single chain (pentane, hexane, etc.).

The ability to pressurize a reservoir to the point of achieving miscibility is, in large part, a function of the magnitude of MMP relative to the maximum pressure at which the reservoir can be pressurized during an EOR project. Accordingly, calculated MMP values were compared to initial reservoir pressures (P_i) and theoretical maximum reservoir pressures (P_{max}) (Table 2.2). In reconstructing the values for P_i, we attempted to document pressures for a reservoir in a field prior to significant production and depletion. P_i values were based on retrievals from the TORIS database or from drillstem or production test data provided at the KGS online database (kgs.uky.edu/kgsweb/DataSearching/oilsearch.asp). Test data were not found for several fields, however, and, consequently, P_i was estimated to equal hydrostatic pressure, which is the pressure exerted by a column of water whose height is proportional to the measured depth of the reservoir. Hydrostatic pressure was estimated by:

$$\text{Hydrostatic pressure } (P_{hydro}) \text{ (psi)} = 0.433 * \text{depth (ft)}.$$

The value for P_{max} was taken from Environmental Protection Agency guidelines (www.epa.gov/r5water/uic/r5guid/r5_07.htm#Ia) and is defined as the maximum pressure a reservoir should attain during injection. It is equal to:

$$P_{max} \text{ (psi)} = 0.8 \text{ psi/ft} * \text{depth (ft)}.$$

The magnitude of P_{max} is intended to keep pressure below that at which fracturing of the reservoir and seal rocks might occur. In the Appalachian and Illinois Basins fracture pressures fall near a gradient of 1.0 psi/ft (Frailey and others, 2004; Nopper and others, 2005). Avoiding fracturing of the seal is important for two reasons. First, it ensures that CO_2 remains in the oil-bearing part of the reservoir, thereby increasing CO_2 interaction with the oil. Second, it facilitates monitoring the fate of the CO_2 and ensures that shallower potable groundwater remains protected.

Reservoir and fluid properties exert significant influence on the viability of reservoirs for combined EOR and sequestration. Using techniques described in Kovscek (2002) and Carr and others (2008), these properties were used to analyze and broadly screen fields in terms of their EOR and sequestration potential. The most fundamental reservoir property is porosity, φ, which is the proportion of rock volume that is open space, typically filled with gas, oil, water, or some combination. Porosity is measured directly from core samples or indirectly from open-hole logs. The initial water saturation, S_{wi}, is the fraction of porosity filled with water at the time that fluids are initially produced

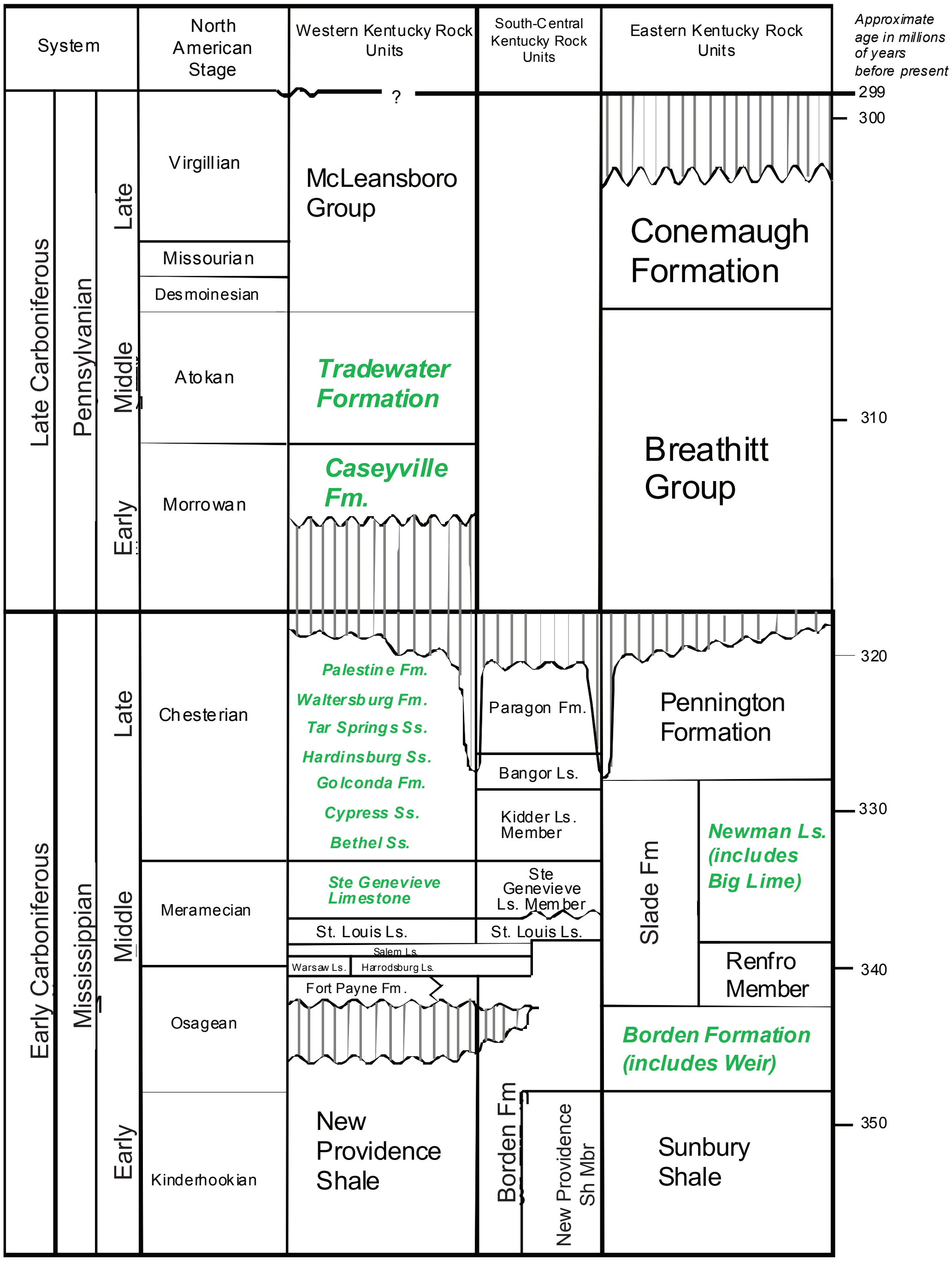

Figure 2.2a. General stratigraphic column showing Pennsylvanian and Mississippian reservoirs of Kentucky. Names in green are reservoirs examined in this study.

from the reservoir and is calculated from open-hole wireline logs. For this study, the fraction of porosity saturated with oil (S_o) was assumed to be $1–S_w$ (in some reservoirs the gas saturation, S_G, must also be considered).

The first screening criterion is the product of oil saturation and porosity, $S_o\varphi$, which is a measure of the amount of oil per unit volume of rock (Table 2.3). Reservoirs having $S_o\varphi$ values greater than 0.05 to 0.07 are often economic for EOR because they started with high initial oil saturations and therefore may have high residual oil saturations. In contrast, reservoirs having values less than 0.05 need to be closely examined for the possibility of additional costs related to EOR

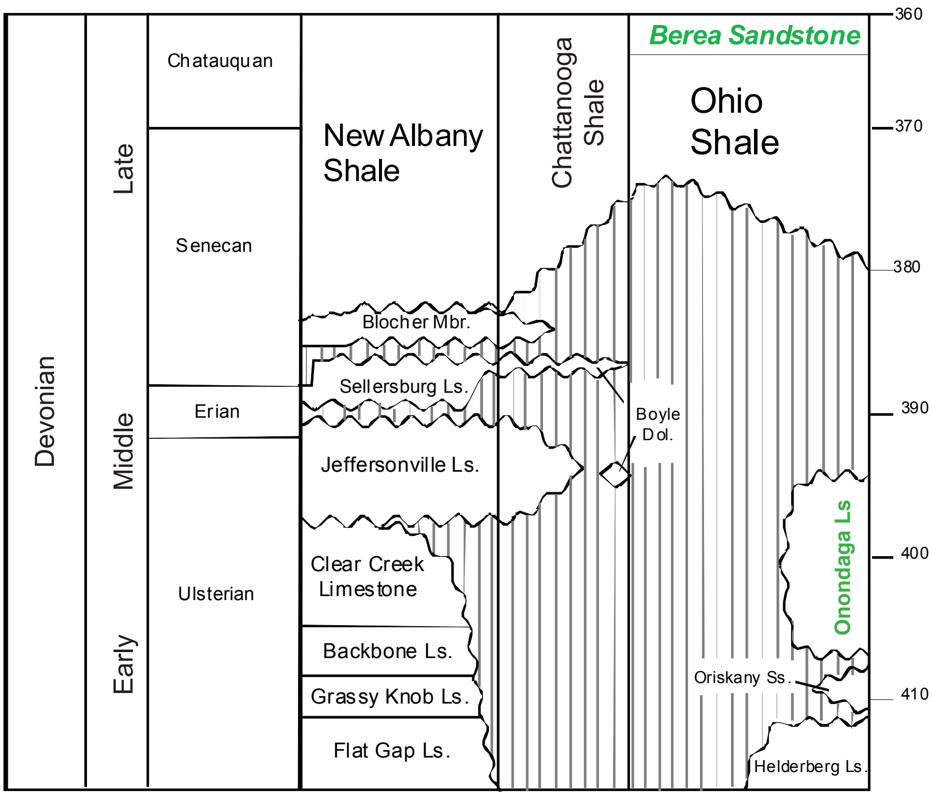

Figure 2.2b. General stratigraphy showing Devonian reservoirs of Kentucky. Names in green are reservoirs examined in this study.

(Kovscek, 2002). From a sequestration perspective, reservoirs having higher $S_o\varphi$ values are more desirable because of a greater potential for a revenue stream from oil sales to offset sequestration costs.

Whereas porosity is a measure of the fraction of pore volume in a rock, the degree to which pore spaces in the rock are interconnected is described by its permeability, *k*. Permeability is a measure of a rock's ability to conduct fluids and is therefore a main rock property influencing the ease of extracting or injecting fluids into a reservoir. To account for permeability, the second screening criterion is defined as the permeability thickness product, *k*h. The net pay thickness, h, is the reservoir thickness (measured in ft) that is sufficiently saturated with oil that it produces economic quantities of oil.[1] According to Kovscek (2002), reservoirs having *k*h values less than 10^{-14} m^3 (33.2427 md/ft) may not have economically viable flow rates for production or injection. Moreover, the product *k*h implies that thick reservoirs having lower permeability can have overall injection rates similar to thinner reservoirs having higher permeability.

The third screening criterion is oil gravity (API gravity or degree API) and provides a measure of how "light" (high API gravity) or "heavy" (low API gravity) an oil is considered. Lighter oils typically are predominated by shorter-chain and volatile hydrocarbons. Heavy oils contain fewer volatiles and are predominantly longer-chain hydrocarbons. By industry standard, API gravity is inversely proportional to the specific gravity of the oil and is determined by:

$$\text{API gravity} = 141.5/\text{specific gravity} - 131.5.$$

The equation demonstrates that oils with lower densities have higher API gravities and tend to flow more readily (have low viscosities). Moreover, miscibility with CO_2 is typically more readily attained with oils having higher API gravities (Jarrell and others, 2002). According to Kovscek (2002), reservoirs having oils with API gravities of less than 22 should be

[1]In this study, permeability is reported in millidarcys and net pay thickness in feet, yielding a permeability-thickness product expressed as md-feet (see Table 2.2). Kovscek (2002), however, used *k* expressed in m^2 and net pay thickness expressed in m. This yields a calculated permeability-thickness product in units of m^3. Multiply *k* in md by 9.869233 X 10^{-16} to obtain *k* in m^2. Multiply *k*h in md-ft by 3.008179 X 10^{-16} to obtain *k*h in m^3.

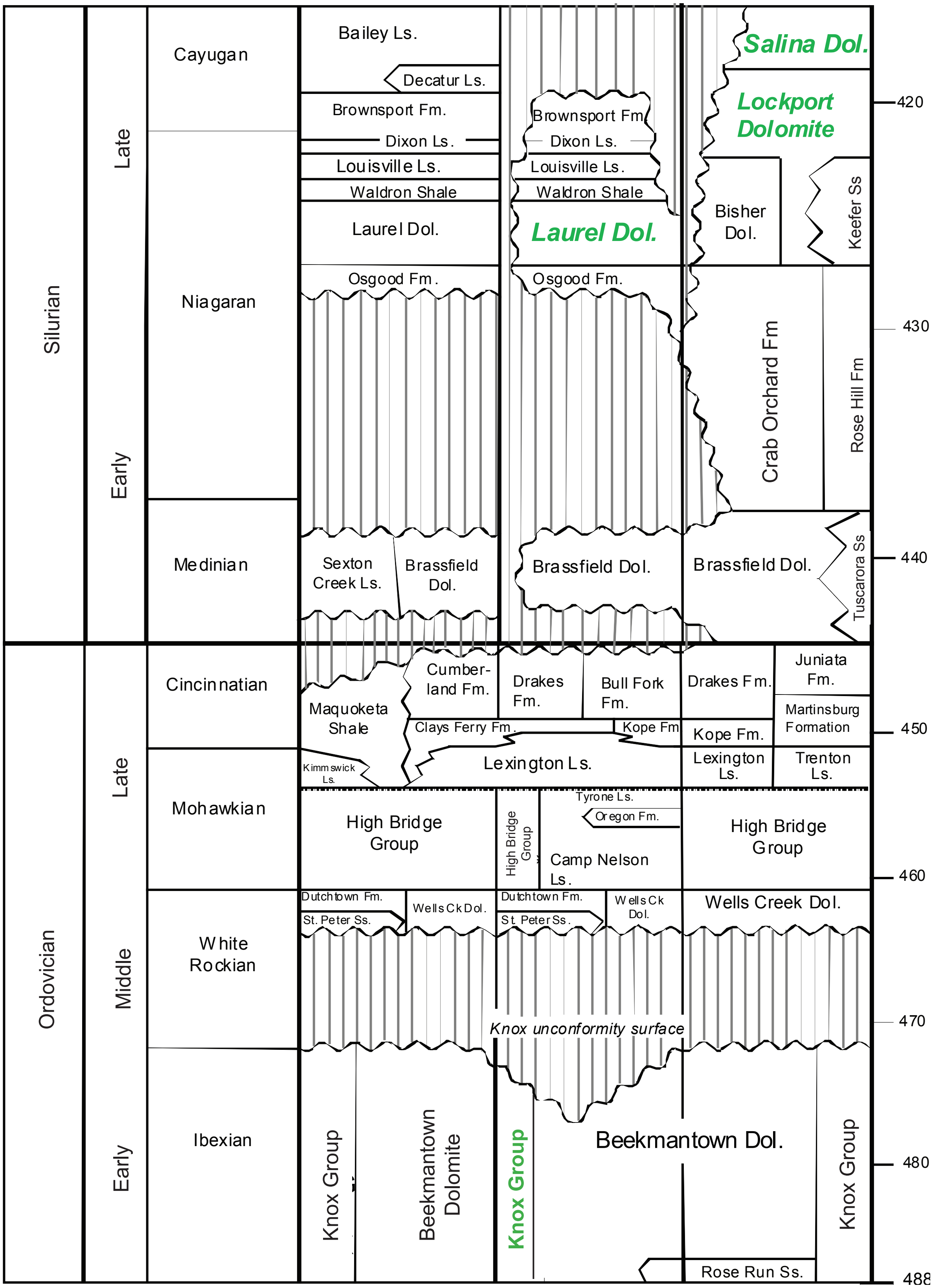

Figure 2.2c. General stratigraphy showing Silurian and Ordovician reservoirs of Kentucky. Names in green are reservoirs examined in this study.

Table 2.2. Measured and calculated pressures. MMP calculated from Cronquist correlation (Bank and others, 2007).

ID	*Initial Pressure, P_i (psi)*	*Current Pressure (psi)*	*MMP* (psi)*	*Fracture Pressure, P_f** (psi)*	*Pi-MMP*	*P_i-P_f*
1	*779.4*	85	839.9	1,080.0	–61	–300.6
2a	300.0	–	1,031.4	429.0	–731	–129.0
2b	*404.4*	–	944.3	560.4	–540	–156.0
3	350.0	50	957.2	546.0	–607	–196.0
4	320.0	50	944.3	621.6	–624	–301.6
5a	500.0	–	1,015.5	898.2	–516	–398.2
5b	*805.4*	–	1,196.6	1,116.0	–391	–310.6
6	460.0	110	880.2	1,410.0	–420	–950.0
7	750.0	215	1,008.0	1,818.0	–258	–1,068.0
8	200.0	174	921.9	1,080.0	–722	–880.0
9	700.0	200	986.9	1,920.0	–287	–1,220.0
10	556.0	490	997.5	1,881.6	–441	–1,325.6
11a	600.0	–	1,150.6	1,366.2	–551	–766.2
11b	*423.0*	–	1,021.8	586.2	–599	–163.2
11c	*769.9*	–	933.0	1,066.8	–163	–296.9
12	300.0	50	820.9	450.0	–521	–150.0
13	370.0	–	922.9	1,050.0	–553	–680.0
14	45.0	–	1,060.5	265.2	–1,016	–
15	450.0	300	1,034.5	1,140.0	–585	–690.0
16a	289.0	–	1,150.6	1,539.6	–862	–1,250.6
16b	632.0	–	993.1	1,234.8	–361	–602.8
16c	117.0	–	1,064.1	1,555.2	–947	–1,438.2
17	*757.8*	–	948.2	1,050.0	–190	–292.2
18	300.0	50	855.0	480.0	–555	–180.0
19	325.0	75	1,008.9	606.0	–684	–281.0
20	320.0	50	992.2	729.0	–672	–409.0
21	300.0	40	996.0	510.0	–696	–210.0
22	*682.8*	–	996.0	946.2	–313	–263.4
23	320.0	40	944.3	540.0	–624	–220.0
24	320.0	50	851.3	480.0	–531	–160.0
25a	555.0	–	1,083.7	843.6	–529	–288.6
25b	712.0	–	1,214.7	1,287.0	–503	–575.0
25c	1,000.0	–	1,132.7	1,569.6	–133	–569.6
25d	703.0	–	1,176.2	1,099.8	–473	–396.8
26	510.0	235	957.2	600.0	–447	–90.0
27	320.0	50	1,073.4	660.0	–753	–340.0
28	*757.8*	–	1,079.1	1,050.0	–321	–292.2
29a	227.0	–	1,150.6	1,065.0	–924	–838.0

Table 2.2. Measured and calculated pressures. MMP calculated from Cronquist correlation (Bank and others, 2007).

ID	*Initial Pressure, P_i (psi)*	*Current Pressure (psi)*	*MMP* (psi)*	*Fracture Pressure, P_f** (psi)*	*Pi-MMP*	*P_i-P_f*
29b	750.0	–	955.0	1,218.0	–205	–468.0
29c	700.0	–	1,214.7	1,536.0	–515	–836.0
30a	725.0	711	976.2	1,404.6	–251	–679.6
30b	*1,141.0*	–	1,085.4	1,581.0	56	–440.0
31	265.0	–	837.2	375.0	–572	–110.0
32a	725.0	–	1,034.5	1,070.4	–310	–345.4
32b	900.0	–	1,071.4	1,342.2	–171	–442.2
33	350.0	–	1,034.5	765.0	–685	–415.0
34	*281.5*	–	833.9	1,144.8	–552	–863.3
35a	*502.7*	–	900.3	696.6	–398	–193.9
35b	*422.2*	–	828.9	530.4	–407	–108.2
36	*1,013.2*	–	1,014.8	1,701.0	–2	–687.8
37a	*372.4*	–	831.6	870.0	–459	–497.6
37b	*336.9*	–	821.4	516.0	–485	–179.1
38	*601.9*	–	968.9	1,041.0	–367	–439.1
39	*751.3*	–	940.1	1,158.0	–189	–406.7
40	*467.6*	–	969.1	1,404.0	–501	–936.4
41a	*646.9*	–	910.3	896.4	–263	–249.5
41b	*433.0*	–	957.6	815.4	–525	–382.4
42a	*826.2*	–	859.6	834.0	–33	–7.8
42b	*738.7*	–	906.2	600.0	–168	138.7
43a	*1,227.6*	–	1,052.7	390.0	–175	837.6
43b	*1,042.7*	–	1,113.2	585.0	–71	457.7
44	*382.8*	–	808.3	466.8	–426	–84.0
45	*516.1*	–	841.8	1,023.6	–326	–507.5
46	*835.7*	–	964.2	1,444.8	–129	–609.1
47	*657.0*	–	990.8	715.2	–334	–58.2
48	*588.4*	–	926.0	1,116.0	–338	–527.6
49	*657.0*	–	1,073.0	1,080.0	–416	–423.0
50	*268.5*	–	902.6	372.0	–634	–103.5
51a	*627.9*	–	937.8	720.0	–310	–92.1
51b	*519.6*	–	986.4	648.0	–467	–128.4

*Italicized initial pressures are calculated hydrostatic pressures = depth (ft) X 0.433 psi/ft
**Fracture pressure (P_r) = fracture gradient (0.6 psi/ft) X depth (ft)

Table 2.3. Reservoir parameters used to evaluate fields for EOR-sequestration.

ID	*(S_o) (ϕ)*	*S_o ϕ*	*Rank $S_o\phi$*	*(k) (h)*	*k*h*	*Rank Kh*	*API Gravity*	*Rank API*	*CO_2 (tons/ac-ft)*	*Rank CO_2 (tons/ac-ft)*	*Sum of Ranks*	*Rank of Sum*	*G CO_s (tons)*
6	(0.72) (0.17)	0.1224	1	(21) (27)	567	52	42.00	1	928.44	2	56	4	2,723,555
10	(0.44) (0.13)	0.0572	44	(21) (23)	483	56	42.00	1	923.40	3	104	13	2,251,974
11b	(0.345) (0.18)	0.0621	40	(308) (10)	3,080	22	40.00	11	291.58	18	91	11	141,722
16a	(0.46) (0.16)	0.0736	25	(58) (8)	464	58	41.00	10	803.21	12	105	15	351,579
30a	(0.47) (0.18)	0.0846	15	(750) (15)	11,250	3	42.00	1	820.60	10	29	1	1,614,908
32a	(0.49) (0.17)	0.0833	19	(150) (20)	3,000	23	36.00	26	293.56	17	85	9	851,593
35a	(0.34) (0.2)	0.0680	27	(309) (16)	4,944	5	37.00	24	196.65	25	81	8	1,467,482
37a	(0.34) (0.2)	0.0680	27	(309) (16)	4,944	5	36.00	26	322.24	15	73	5	548,759
37b	(0.67) (0.14)	0.0938	6	(309) (16)	4,944	5	36.00	26	920.18	4	41	2	9,936,925
39	(0.67) (0.14)	0.0938	6	(309) (16)	4,944	5	36.00	26	822.76	8	45	3	1,202,734
42a	(0.34) (0.2)	0.0680	27	(309) (16)	4,944	5	37.60	21	165.56	36	89	10	533,036
42b	(0.36) (0.15)	0.0540	48	(85) (16)	1,360	33	42.00	1	201.18	23	105	15	298,210
43b	(0.34) (0.2)	0.0680	27	(309) (16)	4,944	5	32.50	63	822.24	9	104	13	474,985
45	(0.34) (0.2)	0.0680	27	(309) (16)	4,944	5	37.80	20	131.03	39	91	11	874,483
46	(0.67) (0.14)	0.0938	6	(309) (16)	4,944	5	36.00	26	114.55	43	80	7	5,352,434
47	(0.34) (0.2)	0.0680	27	(309) (16)	4,944	5	34.39	39	901.73	5	76	6	395,244
1	(0.58) (0.1)	0.0580	43	(60) (9)	540	53	41.80	9	193.06	26	131	32	57,027
2a	(0.2) (0.19)	0.0380	59	(85) (15)	1,275	42	34.00	61	73.98	57	219	70	405,893
2b	(0.21) (0.15)	0.0315	61	(450) (10)	4,500	18	34.39	39	52.98	67	185	61	98,041
3	(0.31) (0.14)	0.0434	55	(34) (20)	680	50	34.39	39	71.43	58	202	66	225,404
4	(0.3) (0.16)	0.0480	53	(45) (22)	990	47	34.39	39	84.20	51	190	64	2,320,549
5a	(0.17) (0.18)	0.0306	62	(102) (15)	1,530	31	38.00	15	185.15	28	136	34	234,841
5b	(0.37) (0.14)	0.0511	49	(1,210) (13)	15,730	1	32.00	64	131.79	38	152	47	690,542
7	(0.43) (0.13)	0.0559	45	(21) (24)	504	55	42.00	1	901.73	5	106	17	3,500,971
8	(0.5) (0.09)	0.0450	54	(60) (15)	900	48	38.00	15	189.36	27	144	42	217,231
9	(0.38) (0.1)	0.0380	59	(21) (16)	336	60	42.00	1	937.99	1	121	28	2,147,619
11a	(0.186) (0.16)	0.0298	63	(38) (16)	608	51	34.39	39	76.62	55	208	68	251,089
11c	(0.38) (0.18)	0.0684	26	(85) (15)	1,275	42	34.39	39	178.68	32	139	40	485,716

Table 2.3. Reservoir parameters used to evaluate fields for EOR-sequestration.

ID	*(S_o) (ϕ)*	*S_o ϕ*	*Rank $S_o\phi$*	*(k) (h)*	*k*h*	*Rank Kh*	*API Gravity*	*Rank API*	*CO_2 (tons/ ac-ft)*	*Rank CO_2 (tons/ ac-ft)*	*Sum of Ranks*	*Rank of Sum*	*G CO_s (tons)*
12	(0.46) (0.18)	0.0828	20	(8) (20)	160	66	40.00	11	57.29	66	163	53	113,435
13	(0.51) (0.12)	0.0612	41	(2) (15)	30	70	37.30	23	180.77	29	163	53	715,836
14	(0.09) (0.12)	0.0108	69	(642) (12)	7,704	4	34.39	39	30.89	70	182	59	139,656
15	(0.43) (0.1)	0.0430	57	(100) (16)	1,600	29	36.00	26	199.64	24	136	34	319,422
16b	(0.18) (0.14)	0.0252	66	(75) (14)	1,050	44	34.39	39	835.68	7	156	51	1,431,560
16c	(0.12) (0.12)	0.0144	67	(105) (10)	1,050	44	39.00	13	224.86	20	144	42	1,214,352
17	(0.54) (0.1)	0.0540	47	(60) (9)	540	53	36.00	26	180.77	29	155	50	164,641
18	(0.31) (0.14)	0.0434	55	(300) (14)	4,200	19	38.50	14	61.61	64	152	47	526,615
19	(0.38) (0.16)	0.0608	42	(4) (25)	100	67	34.39	39	80.10	53	201	65	397,314
20	(0.44) (0.2)	0.0880	13	(11) (25)	275	64	38.00	15	99.58	45	137	37	549,662
21	(0.45) (0.17)	0.0765	24	(5) (56)	280	63	34.39	39	65.18	61	187	62	2,327,046
22	(0.55) (0.1)	0.0550	46	(60) (15)	900	48	34.39	39	149.40	37	170	57	486,696
23	(0.48) (0.17)	0.0816	22	(8) (36)	288	62	34.39	39	70.71	59	182	59	380,819
24	(0.5) (0.18)	0.0900	12	(12) (30)	360	59	38.00	15	61.80	63	149	45	180,209
25a	(0.46) (0.17)	0.0782	23	(309) (12)	3,708	20	36.00	26	119.32	41	110	20	84,490
25b	(0.46) (0.18)	0.0828	20	(184) (14)	2,576	25	34.39	39	175.19	34	118	23	518,190
25c	(0.42) (0.16)	0.0672	37	(58) (23)	1,334	41	34.39	39	230.78	19	136	34	409,135
25d	(0.35) (0.14)	0.0490	52	(105) (15)	1,575	30	36.00	26	813.44	11	119	25	638,742
26	(0.36) (0.14)	0.0504	51	(2) (30)	60	68	34.39	39	80.23	52	210	69	137,153
27	(0.46) (0.19)	0.0874	14	(10) (25)	250	65	34.39	39	87.59	49	167	56	2,357,058
28	(0.551) (0.1)	0.0510	50	(60) (8)	480	57	30.80	70	180.77	29	206	67	37,310
29a	(0.17) (0.17)	0.0289	64	(200) (17)	3,400	21	34.39	39	223.01	22	146	44	401,607
29b	(0.16) (0.16)	0.0256	65	(24) (14)	336	60	42.00	1	168.14	35	161	52	1,351,488
29c	(0.1) (0.14)	0.0140	68	(800) (15)	12,000	2	34.39	39	492.01	13	122	29	816,154
30b	(0.066) (0.15)	0.0099	70	(105) (13)	1,365	32	38.00	15	339.36	14	131	32	805,044
31	(0.44) (0.21)	0.0924	11	(95) (19)	1,805	28	42.00	1	45.98	69	109	18	310,051
32b	(0.37) (0.18)	0.0666	38	(150) (20)	3,000	23	36.00	26	177.00	33	120	26	1,087,450
33	(0.3) (0.14)	0.0420	58	(25) (40)	1,000	46	36.00	26	106.17	44	174	58	2,217,125

Table 2.3. Reservoir parameters used to evaluate fields for EOR-sequestration.

ID	*(S_o) (ϕ)*	*S_o ϕ*	*Rank $S_o\phi$*	*(k) (h)*	*k*h*	*Rank Kh*	*API Gravity*	*Rank API*	*CO_2 (tons/ ac-ft)*	*Rank CO_2 (tons/ ac-ft)*	*Sum of Ranks*	*Rank of Sum*	*G CO_s (tons)*
34	(0.34) (0.2)	0.0680	27	(309) (16)	4,944	5	34.39	39	92.31	47	118	23	121,248
35b	(0.7) (0.16)	0.1120	2	(85) (16)	1,360	33	34.39	39	92.96	46	120	26	578,078
36	(0.67) (0.14)	0.0840	16	(85) (16)	1,360	33	36.00	26	92.31	47	122	29	649,158
38	(0.67) (0.14)	0.0938	6	(150) (16)	2,400	26	32.70	62	224.15	21	115	21	522,818
40	(0.45) (0.14)	0.0630	39	(2) (23)	46	69	31.00	65	297.00	16	189	63	73,843
41a	(0.67) (0.14)	0.0938	6	(150) (16)	2,400	26	31.00	65	125.48	40	137	37	2,057,343
41b	(0.67) (0.14)	0.0840	16	(85) (16)	1,360	33	36.00	26	64.40	62	137	37	1,149,154
43a	(0.7) (0.16)	0.1120	2	(85) (16)	1,360	33	37.00	24	84.83	50	109	18	630,443
44	(0.7) (0.16)	0.1120	2	(85) (16)	1,360	33	37.60	21	70.10	60	116	22	686,672
48	(0.67) (0.14)	0.0840	16	(85) (16)	1,360	33	34.39	39	118.19	42	130	31	406,466
49	(0.34) (0.2)	0.0680	27	(309) (16)	4,944	5	31.00	65	77.14	54	151	46	361,224
50	(0.34) (0.2)	0.0680	27	(309) (16)	4,944	5	31.00	65	46.73	68	165	55	220,330
51a	(0.34) (0.2)	0.0680	27	(309) (16)	4,944	5	31	65	74.80	56	153	49	563,167
51b	(0.7) (0.16)	0.1120	2	(85) (16)	1,360	33	34.39	39	57.31	65	139	40	3,996,011

scrutinized because miscibility with CO_2 and flow rates will be diminished.

The final ranking criterion is a measure of the theoretical effective storage capacity (ESC) in short tons of CO_2 per acre-ft of volume of each reservoir, expressed as:

$$\text{ESC (kilotons)} = 43{,}560 * \varphi * \rho * S_o * 0.001$$

where 43,560 is a constant equal to the volume of 1 acre of reservoir 1 ft thick and is used to convert density in short tons/ft^3 to density in short tons/acre-ft, ρ is the density of CO_2 in short tons/ft^3 at estimated reservoir conditions, and 0.001 is a conversion to kilotons. CO_2 in a reservoir may occur in any one of three phases (gaseous, liquid, and supercritical fluid), depending upon reservoir pressure and temperature, which are, in turn, proportional to depth. Given a unit volume of reservoir rock (an acre-ft), the storage capacity is an important function of CO_2 density and thus, by means of the hydrostatic and geothermal gradients, is an indicator of the relationship between ultimate storage capacity and reservoir depth.

To describe the total amount of CO_2 that can be stored in oil and gas reservoirs during and after the main phase of EOR, the mass was calculated using the equation adopted by the Capacity and Fairways Subgroup of the Geologic Working Group for the U.S. Department of Energy Regional Carbon Sequestration Partnerships (Carr and others, 2008):

$$G_{CO2} = A * h_n * \varphi * S_o * \rho * B * E, \text{ or effectively}$$
$$G_{CO2} = A * h_n * ESC * B * E$$

where A = area (acres), h_n = height of oil and gas column in the reservoir (i.e., net pay), φ = average reservoir porosity, S_o = oil saturation (i.e., total reservoir volume available for CO_2 storage assuming 100 percent displacement of oil), ρ = density of CO_2 at expected reservoir conditions (short tons/acre-ft), B = formation volume factor, which converts standard oil or gas subsurface volume at formation pressure and temperature (a value of 1 was used in this study), and E = estimated displacement efficiency of CO_2 with respect to all pore fluids. The density of CO_2 (ρ) was calculated using the National Institute of Standards and Technology (2008) online webbook for thermophysical properties (webbook.nist.gov/chemistry/fluid/). The displacement efficiency, E, and formation volume factor, B, were both assumed to equal 100 percent (i.e., 1.0) for all reservoirs considered; therefore, values for G_{CO2} represent theoretical maxima.

By definition, there is a direct relation between the ESC and G_{C02} for a reservoir. The effective storage capacity was selected as a comparison and evaluation criteria because the gross reservoir capacity, can be misleading. A reservoir with a large areal extent and large gross capacity is not necessarily superior to a smaller reservoir in which higher-density phases of CO_2 may be stored.

In this analysis, larger values for each of the screening criterion correspond to reservoir properties that are more favorable for CO_2-EOR. This relationship was used to rank the fields for each of the screening criteria. For example, the highest API gravity observed in the study was 42°, and fields having oils with this value were assigned a rank of 1 for this criterion (Table 2.1). The ranking values for each screening criteria were summed (Table 2.3, Sum of Ranks) to provide an aggregate ranking of the 70 reservoirs. Reservoirs having low sum of rank values should accordingly be more favorable for CO_2-EOR. For analysis and plotting purposes, fields were divided into quartiles based on their sum of rank values.

Results

The majority of fields and reservoirs in this study are shallow, with 87 percent at 2,500 ft or shallower. When analyzed versus depth, 90 percent of the fields have pressures less than hydrostatic and are therefore underpressured (Fig. 2.3). The apparent widespread distribution of underpressured fields underscores the importance of the relationship among P_i, MMP, and P_{max} within the context of evaluating fields for EOR potential. The relationship between P_i and MMP is shown schematically in Fig. 2.4, in which the black reference line represents the condition of P_i being equal to MMP. The fields show a wide range of values for P_i, but MMP values plot in a relatively narrow interval of 800 to 1,200 psi. The narrow range for MMP is accounted for by the relatively narrow range of temperatures (68–92°F) and API oil gravities (31–42°) that were input into the Cronquist correlation. The critical point demonstrated by Fig. 2.4 is that, with the exception of the Birk City field–Ste. Genevieve reservoir in Daviess and Henderson Counties, all of the fields plot in the area in which P_i is less than MMP; that is, above and to the left of the one-to-one line. The corollary to this observation is that practically all of the fields would not reach pressures sufficient for miscibility if the reservoirs were simply repressurized to the values for P_i (negative values for P_i-MMP in Table 2.2). If, however,

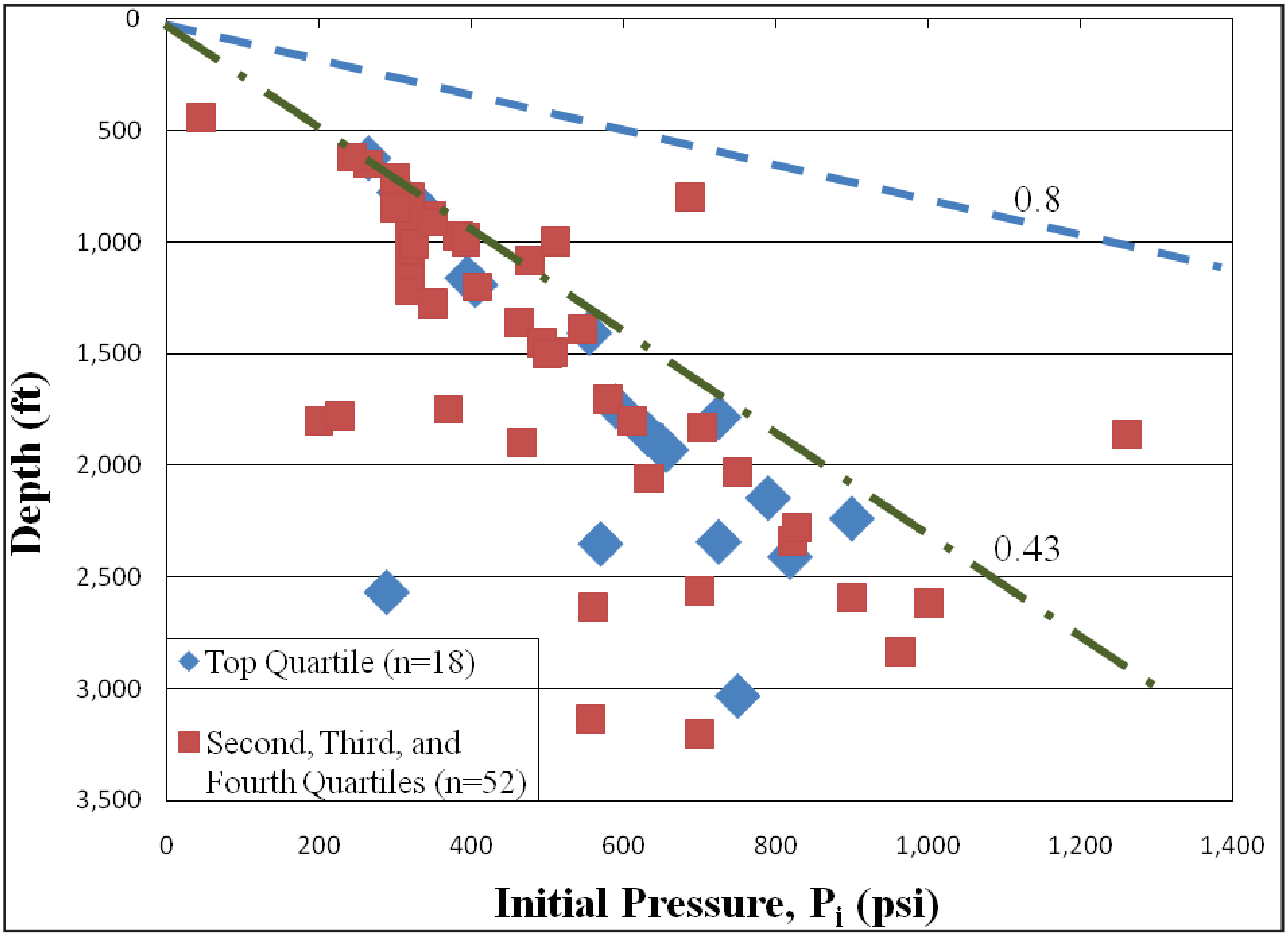

Figure 2.3. Initial reservoir pressure versus measured depth for fields (n = 40) in which pressures were documented before significant depletion.

the magnitude of repressurization equaled P_{max}, then 63 percent of the fields would have pressures that exceeded the MMP values (Fig. 2.5, positive values for P_{max} – MMP in Table 2.2). Importantly, pressurization in the fields where P_{max} is greater than MMP would produce reservoir conditions conducive to miscibility between CO_2 and oil.

Our analysis shows that 18 fields-reservoirs make up the upper quartile in terms of their aggregate score ("Sum of Ranks," Table 2.3), based on reservoir and oil properties favorable for CO_2-EOR sequestration. The Big Lime reservoir in the Bulan and Bull Creek Fields in eastern Kentucky is the only carbonate reservoir represented in the upper quartile. Of the remaining clastic fields, 83 percent are Mississippian Chester sandstones belonging to the Waltersburg, Hardinsburg, Bethel, and other reservoirs in western Kentucky.

Nearly 67 percent of the reservoirs in the upper-quartile fields occur at 1,500 ft or deeper (Fig. 2.3). Within the context of potential miscibility, all of the fields, except three, have values for P_{max} that exceed MMP (Fig. 2.3, Table 2.2). The three fields-reservoirs for which this relative pressure relation does not hold include the Chester sandstones in the Taffy and Cane Run Fields in western Kentucky. The Chester sandstone reservoirs in these fields are less than 1,000 ft deep.

Discussion

The analysis and ranking of fields into quartiles represents the composite influence of multiple reservoir and fluid properties (Table 2.3). Because the ranking criteria were taken from sources (Kovscek, 2002; Carr and others, 2008) that analyzed EOR and sequestration in a broader and more general context, we felt it

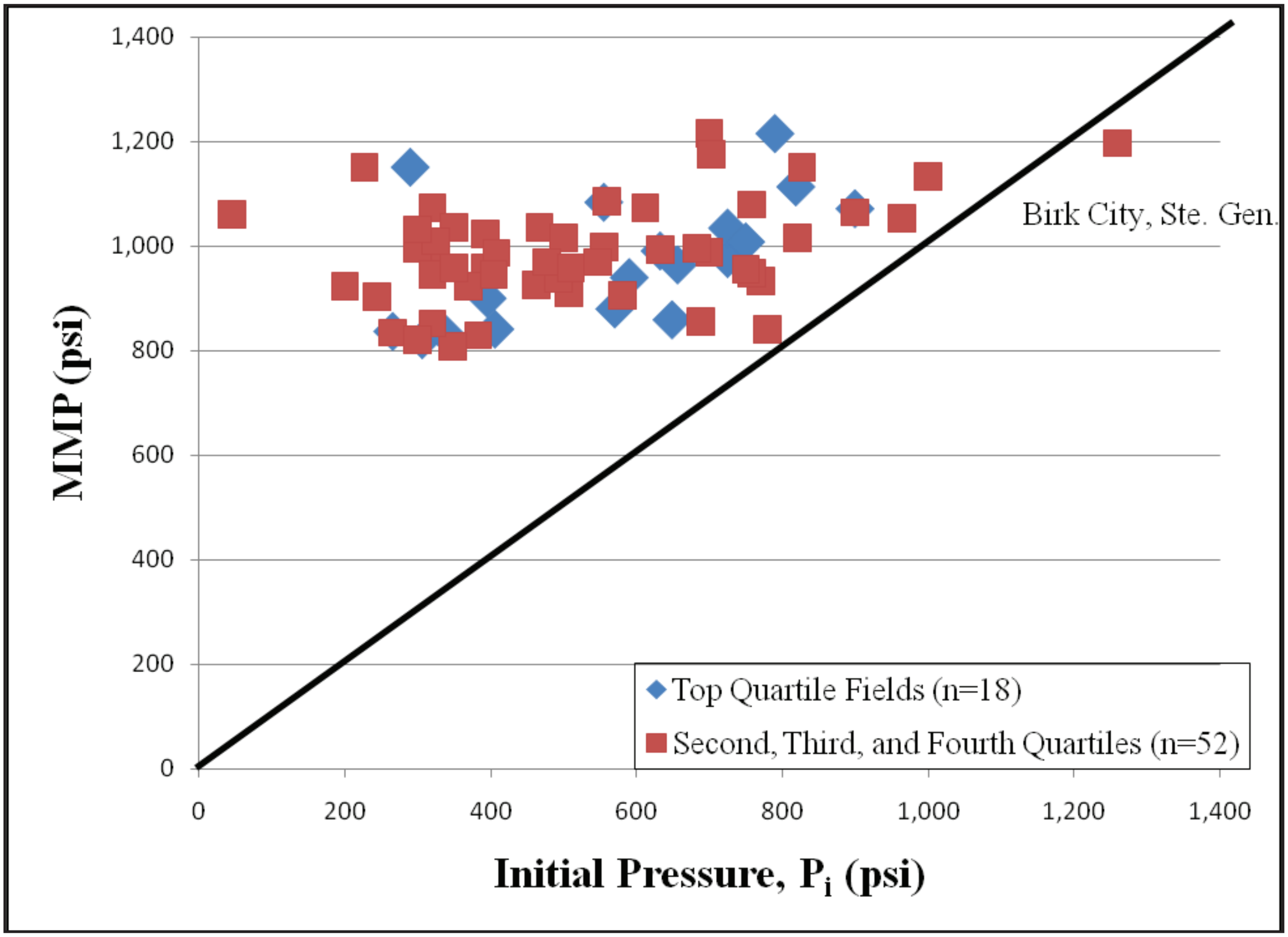

Figure 2.4. Relative relationship between P_i and MMP for fields-reservoirs. The black line is a one-to-one relationship between P_i and MMP. Only one reservoir lies below this line, suggesting that it may be near-miscible. Fields that lie above the line are likely immiscible.

was important to determine which criterion or criteria tended to characterize fields in the upper versus lower quartiles. Going forward, recognition of such criteria might assist in analysis of other fields in and outside of Kentucky not analyzed in this study. The distributions of fields in the upper versus lower three quartiles were first analyzed for each of the four screening criteria (Table 2.3). The distribution of the criterion, ln(kh), provides a representative example in which fields-reservoirs in the upper quartile plot at higher values, whereas fields-reservoirs in the lower three quartiles tend to be distributed across the full range of values (Fig. 2.5). If the distribution of ln(kh) is truly representative of the other screening criteria, this suggests that no single criterion can be used to define fields-reservoirs most prospective for EOR-sequestration. Alternatively, if pairs of screening criteria are related, then cross-plots of those criteria might exhibit distinct clusters that group into quartile populations. To investigate this hypothesis, the covariance of each of the screening criteria was calculated. The variances along the main diagonal of that matrix were used to calculate the correlation coefficients between each pair of parameters (Davis, 1986, p. 34–41). Table 2.4 is the lower half of the correlation coefficient matrix, the main diagonal of which indicates the perfect correlation of each individual parameter distribution with itself. Table 7 of Crow and others (1960, p. 241) indicates that the only statistically valid correlation ($r=0.3235$) is between the natural log of the CO_2 storage capacity in short tons/acre-ft and the API gravity (significant at the 95 percent level of confidence, $\alpha=0.05$). Figure 2.6 shows the distribution of the natural log of the permeability thickness product in the top quartile. Figure 2.7 is a cross-plot of these parameters, and although the top-quartile-ranked fields generally occur to the upper right

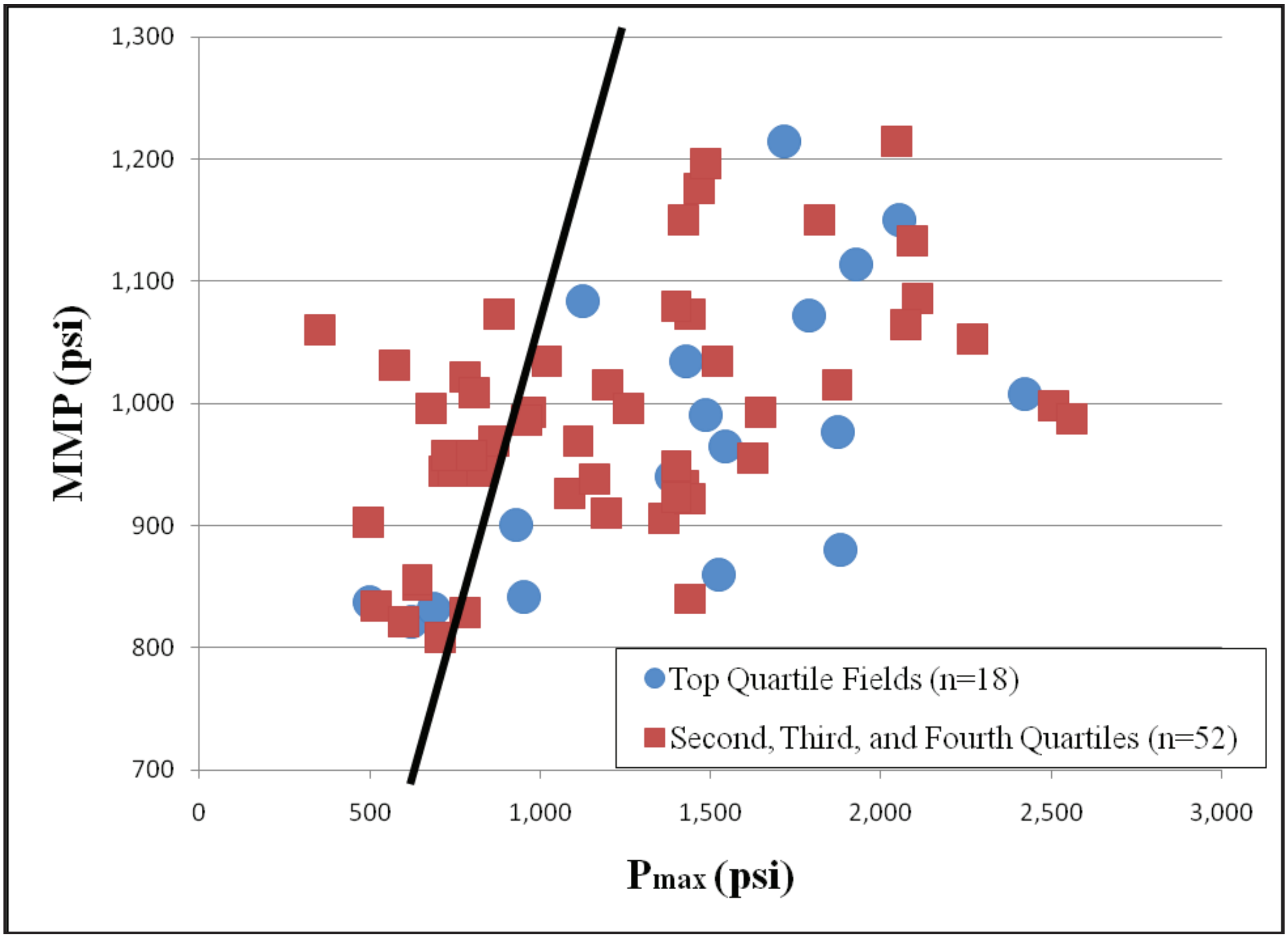

Figure 2.5. Relative relationship between P_i and P_f for fields-reservoirs. The black line is a one-to-one relationship between P_i and P_f. Note that three reservoirs fall below this line and one lies on the line, indicating these reservoirs may be brought up to the initial pressure without fracturing the reservoir rock (their P_i < Pf), whereas the other reservoirs lie above the line, indicating they cannot be brought up to initial reservoir pressure without fracturing the reservoir rock (their $P_i > P_f$).

of the chart, the scatter is a clear indication of the generally poor correlation.

In the absence of screening criteria that individually or as pairs clearly distinguish a particular oil field as being better than another for CO_2-EOR, all of the assessed parameters must be evaluated subjectively. If each of the four main screening criteria is divided along quartile boundaries, the higher-ranked fields tend to have two or more assessed criteria in the top quartile of the distribution, whereas the other fields have two or fewer criteria in their respective top quartiles. The top-quartile fields also tend to have zero or one criterion in the lowermost (less than 25 percent) quartile for that criterion. The ranking of a field (Table 2.3, Rank of Sums) thus represents the composite and complex influence of the four screening criteria. Because of this, we recommend that not too much emphasis be put on the absolute score of any given field, but rather on where that field falls in the broader quartile distribution.

Estimation of CO_2 storage capacity was one of the study objectives (Table 2.3, GCO_2). Because storage capacity was not used in the ranking process, many fields with large estimated capacities relative to the other fields did not fall into the upper quartile; for example, the Tar Springs reservoir in the Utica Field (ID 51b) equals 4,405,000 short tons. For all fields in the upper quartile, total estimated CO_2 storage capacity equals 35,088,000 short tons. This mass represents 44 percent of the capacity (79,134,000 short tons) for all of the analyzed fields. The values for GCO_2 in Table 2.3, however, represent theoretical maxima, and actual storage capacities could be significantly lower by half or more. The reason for the large potential error is because of the efficiency factor, E, which was assumed to equal 1.0, representing 100 percent displacement efficiency of the oil. We recognize that this assumption is grossly overly simplistic, but more meaningful measures of E will require determination of factors such as irreducible water saturation, partitioning of CO_2 between the free phase and dissolution in water, and sweep efficiency.

The complex interplay among the screening criteria in deciphering which fields are most prospective for CO_2-EOR and sequestration underscores the importance of reservoir pressure relative to MMP. As noted, approximately 63 percent of the analyzed fields have values of P_{max} that are greater than MMP and therefore could attain miscible or near-miscible conditions if the reservoirs were pressurized to values equal to P_{max} (Fig. 2.5). Over the course of an EOR project, the increase to pressures equal to P_{max} will be transient, with a pressure decay occurring upon cessation of CO_2 injection. Nevertheless, care should be taken that during injection reservoir pressures do not exceed values for P_{max} and certainly not pressures equal to those at a lithostatic gradient at 1.0 psi/ft, along which reservoir and seal rocks are more likely to be fractured. Improved characterization of reservoir pressure can be attained using pressure transient tests on injection and production wells (Jarrell and others, 2002).

Many fields in Kentucky have used waterfloods as a method to recover additional oil. The response of the reservoir during the waterflood may provide important information on how it will respond using CO_2 as a tertiary recovery method. Specifically, waterflood response can provide information on reservoir heterogeneity related to facies changes or structural discontinuities. Such heterogeneities will affect sweep efficiency of the injected CO_2, and placement of injection and production wells should be guided by this information along with other pertinent geologic and engineering data (e.g., geologic structure). As a rule of thumb, good waterfloods may indicate a good CO_2-EOR project; however, a bad waterflood will most likely produce an even worse CO_2 flood (Jarrell and others, 2002). The potentially significant difference between the performance of a waterflood and CO_2-EOR projects results from the lower viscosity and density of CO_2, which make it buoyant and more mobile in the reservoir.

Because fields in Kentucky tend to be under-pressured and below the MMP values needed to attain miscibility (Fig. 2.5), it might be appropriate to implement a waterflood prior to CO_2 injection. In doing so, the reservoir would be largely pressurized with water, allowing subsequently injected CO_2 to better interact with the oil. Injection of water before or after CO_2 injection (water-alternating-gas; WAG) should be done with caution inasmuch as it might change the formation wettability characteristics and prevent CO_2 from contacting oil in the reservoir (Jarrell and others, 2002).

Other factors that should be considered and tasks to be undertaken when evaluating a CO_2-EOR project include, for example, source of CO_2, reservoir modeling to predict incremental oil recovery, economic forecasting, infrastructure, and logistics. Consideration of these factors is beyond the scope of this report; refer to Jarrell and others (2002) for a comprehensive treatment. Plugging standards have changed over time; many wells considered properly abandoned for their time may not meet modern standards. Moreover, there is the issue of wells that were illegally or improperly abandoned. Improperly plugged and abandoned wells, along with producing wells with poor cement jobs, represent possible pathways for injected or stored CO_2 to migrate to the surface. This is an issue for the obvious reasons of project safety and protecting groundwater quality, but also because fugitive CO_2 is not available to enhance oil recovery. The issue of leaking wellbores is especially critical for CO_2-EOR projects that might be conducted as pattern floods with multiple producing wells. The issue is less critical for single-well cyclic projects, although with a large-volume CO_2 injection it is possible that the radius of influence could extend into the surrounding wells. Thus, confirmation of good wellbore integrity should be a fundamental part of any planned CO_2-EOR project, and contingencies should be made for possible wellbore remediation.

Summary

1. Seventy oil reservoirs in 51 oil fields from the Illinois Basin, Appalachian Basin, and central Kentucky were analyzed for their potential for CO_2-EOR and CO_2 storage.
2. Analysis of initial reservoir pressures (P_i) using data mostly from the TORIS database, and drillstem and production test data from the KGS online database, show that most (90 percent) Kentucky oil reservoirs were under-pressured (that is, below hydrostatic pressure) even before pressures were reduced as a result of production, Moreover, initial

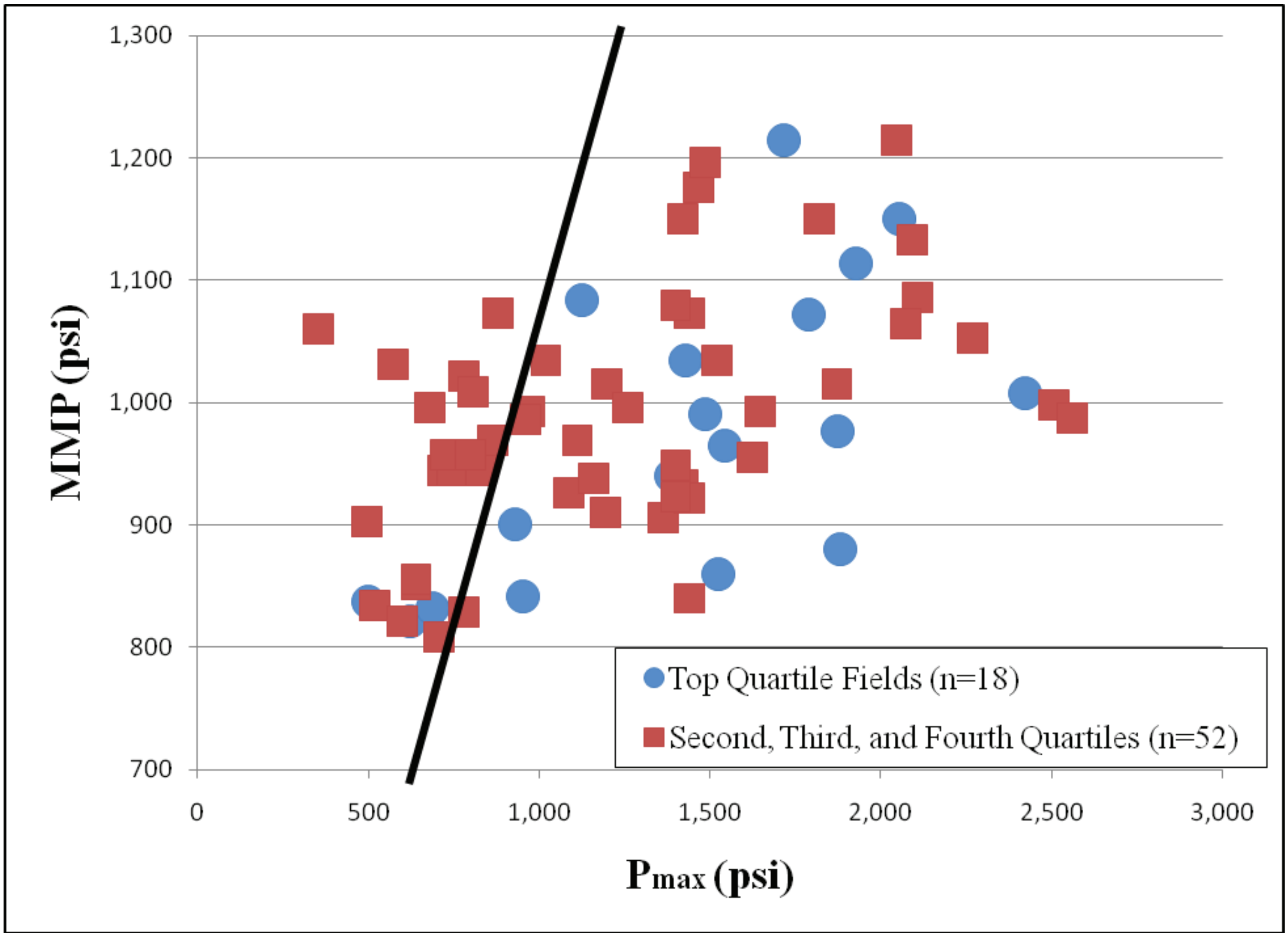

Figure 2.6. Relative relationship between P_{max} and MMP for fields-reservoirs. The black line is a one-to-one relationship between P_{max} and MMP. Fields to the right of the black line might reach miscible or near-miscible conditions with pressurization to P_{max}, whereas fields to the left will mostly remain immiscible.

Table 2.4. Correlation coefficients, r, of each pair of assessment parameters (Kovscek, 2002).

r	*So*ϕ*	*ln (tons/ac-ft)*	*ln (kh)*	*API*
*So*ϕ*	1.0000			
ln (tons/ac-ft)	–0.0743	1.0000		
ln (kh)	–0.0064	0.0827	1.0000	
API	0.0050	0.3235	–0.1721	1.0000

reservoir pressures were well below the calculated minimum miscibility pressures.

3. If, however, reservoir pressures are increased to a magnitude equal to the recommended maximum allowable injection pressure (P_{max}) as defined by the U.S. Environmental Protection Agency, 53 percent of the fields would have pressures sufficient to attain miscible or near-miscible conditions.
4. The reservoir and fluid parameters $S_o\varphi$, *k*h, API oil gravity, and CO_2 storage capacity, as defined by Kovscek (2002) and Carr and others (2008), were used to assess and rank fields into quartiles based on their potential for CO_2-EOR and CO_2 storage.

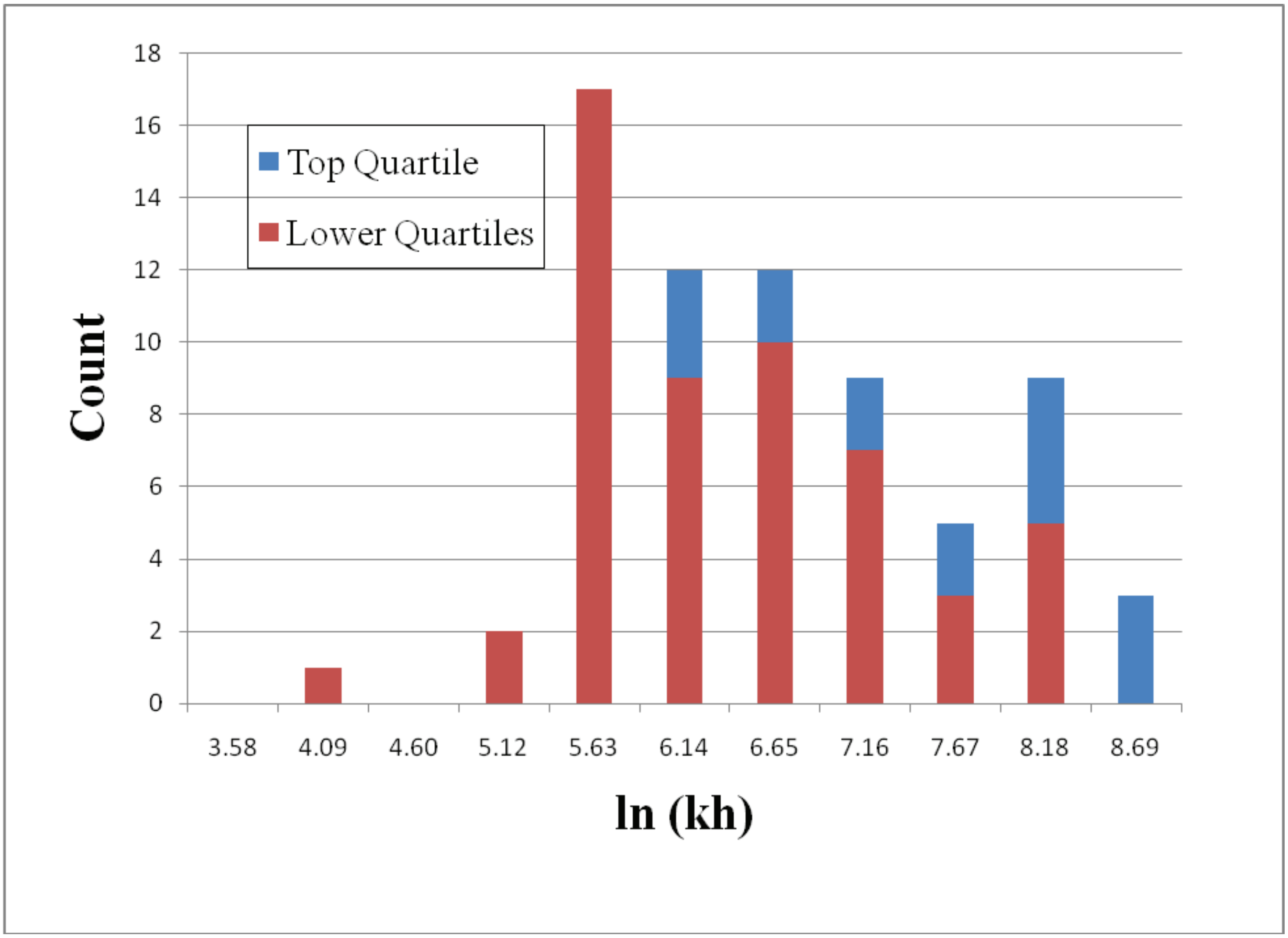

Figure 2.7. Distribution of the natural log of the permeability thickness product showing counts of top-quartile values.

5. Of the 18 fields-reservoirs in the upper quartile, 83 percent are in Mississippian Chesterian sandstone reservoirs in western Kentucky. Sixty-seven percent of the upper quartile fields occur at depths of 1,500 ft or deeper and 83 percent have values for P_{max} that exceed MMP.
6. Statistical analysis of the ranking parameters shows that no single parameter or combination of two parameters accounts for fields being ranked in the top quartile. Instead, top-quartile ranking appears to result from the composite influence of all ranking parameters.
7. Gross estimated CO_2 storage capacity in all analyzed fields-reservoirs (n=70) equals 79,134,000 short tons, of which 44 percent (35,088,000 short tons) occurs in the upper-quartile fields.

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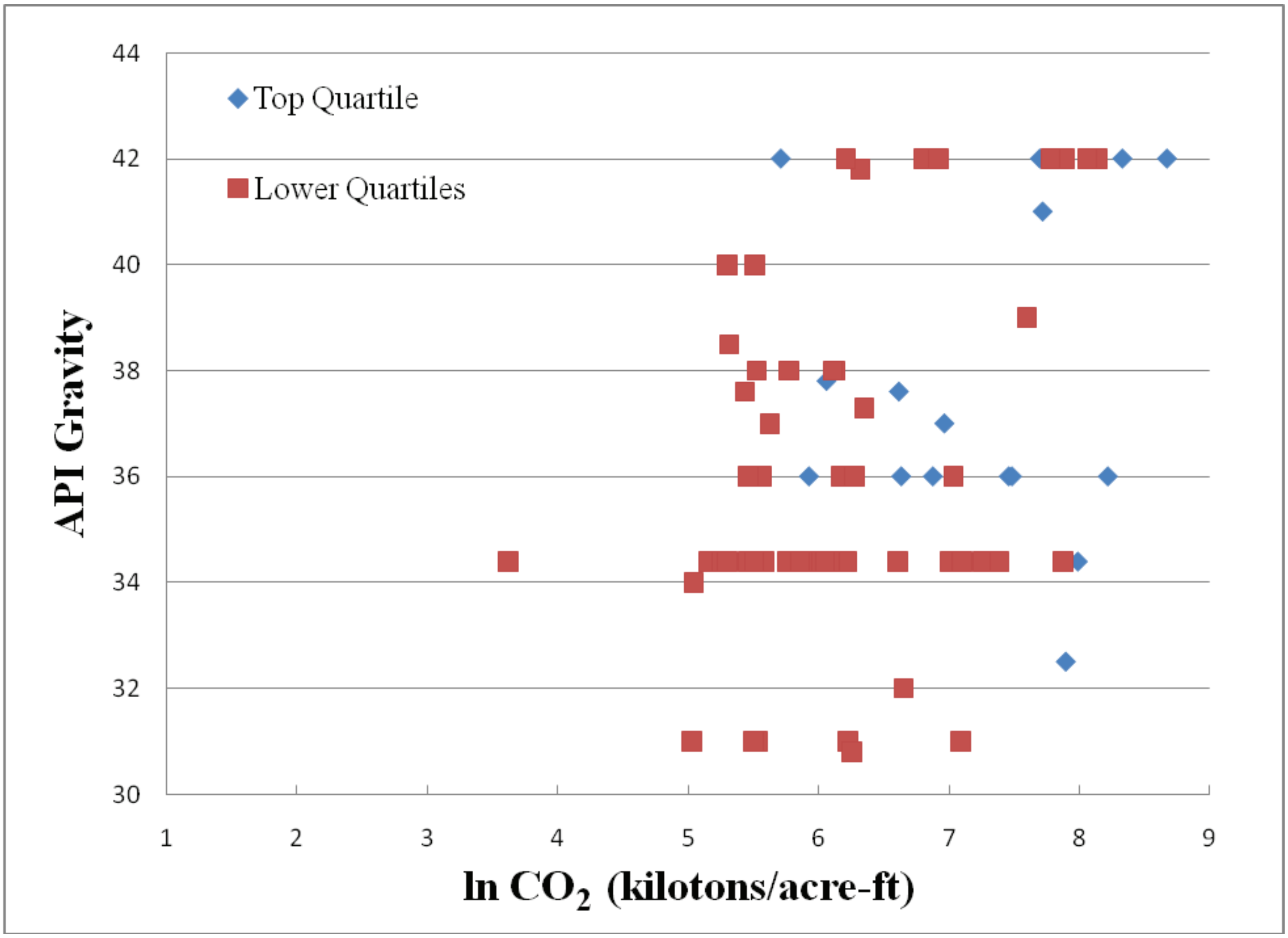

Figure 2.8. Cross-plot of CO_2 storage capacity (short tons/acre-foot) and API gravity.

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Chapter 3: Geochemical Characterization of Formation Waters in Kentucky and Implications for Geologic Carbon Storage

Thomas M. Parris, Donna J. Webb, Kathryn G. Takacs, and Nick Fedorchuk

Introduction

With an estimated worldwide capacity of at least 1,100 billion short tons, deep saline aquifers are volumetrically the most significant reservoir for storage of CO_2 in underground geologic reservoirs (Holloway, 2001). Once in the reservoir, CO_2 can be stored or trapped in a variety of modes, including physical trapping beneath a low-permeability seal (e.g., shale, salt), retention as an immobile phase in pore space (residual trapping), dissolution into the formation fluids (solubility trapping), and involvement in mineral-forming reactions (mineral trapping). The chemistry of waters in the storage reservoir—formation waters—will be one of the main influences on solubility and mineral trapping. Over shorter periods of tens to hundreds of years in which a geologic storage project would be monitored, solubility trapping will be especially important because dissolution of CO_2 into water will be one of the fastest reactions to occur in the reservoir (Kharaka and others, 2006). Though volumetrically not as significant as injection of CO_2 into saline reservoirs for storage, injection of CO_2 into oil reservoirs for enhanced oil recovery represents another storage possibility. The magnitude of CO_2 dissolution in the formation waters will affect the degree to which CO_2 is available for interaction with the oil.

The importance of formation-water chemistry in geologic carbon storage provided the motivation for this study, which used heretofore archived formation-water chemistry data that have been effectively out of the public domain for more than 20 years. Specifically, we analyzed the stratigraphic and depth distribution of dissolved constituents in formation waters from the Illinois Basin in western Kentucky and Appalachian Basin in eastern Kentucky to make inferences about hydrogeologic compartmentalization and sealing in Paleozoic strata. To estimate CO_2 solubility trapping potential, temperature, pressure, and chemistry data were used as inputs to calculate CO_2 solubility with an equation of state for aqueous solutions containing Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-}.

Methods

Data constituting the foundation for this study came from 356 analyses of formation-water chemistry collected primarily from oil wells and a smaller number of waste-disposal and water wells (Table 3.1). The data came from 12 counties in western Kentucky and 11 counties in eastern Kentucky. Geologically, the analyses provide a record of formation-water chemistry from the Illinois and Appalachian Basins, respectively (Figs. 3.1–3.2). The data were part of archived paper records at the Kentucky Geological Survey, and individual analyses were recorded on USGS-format water data sheets. Chemistry data on the USGS sheets typically included cation and anion concentrations reported in mg/L; water property measurements such as pH, conductivity, density, and total dissolved solids (TDS); and administrative data such as well name and operator, Carter coordinate location, depth and stratigraphic interval sampled, and location at the surface where the sample was collected (Fig. 3.3). Many of the samples were collected in the late 1960's and early 1970's, but the motivation for their collection is unknown.

Stratigraphically, the water samples were collected from rocks that range in age from Precambrian to Pennsylvanian; most are Mississippian (61 percent) in the Illinois Basin and Mississippian and Pennsylvanian (69 percent) in the Appalachian Basin (Figs. 3.4–3.5). In both basins the fewest samples came from Ordovician and older rocks. Approximately 51 percent and 70 percent of samples from the Illinois and Appalachian Basins, respectively, were collected from clastic reservoirs such as the St. Peter, Cypress, Jackson, and Caseyville sandstones. With the exception of about 13 percent of New Albany Shale samples from the Illinois Basin, the remaining samples from both basins were collected from carbonate reservoirs such as the Knox, Laurel, McClosky, and Fort Payne (Table 3.1). The samples span a depth range of 579 to –7,605 ft in eastern Kentucky and 1,550 to –7,765 ft in western Kentucky (depths referenced to sea level). The deepest water sample in western Kentucky, collected from the DuPont WAD No. 1 well in Jefferson County, is from the Cambrian Mount Simon or basal sandstone.

Table 3.1. Summary of water analyses by depth and general stratigraphic unit. Depth ranges are referenced to sea level. The "Example Formations" column lists the most frequently encountered specific stratigraphic units within each broad "Age–Rock Type" category. "Carbonate" refers to a mixture of limestone and dolomite. Where combined, the first abbreviation is the dominant rock type.

Age–Rock Type	*No. of Analyses*	*Depth Range (ft)*	*Example Formations*
Illinois Basin			
Pennsylvanian sandstone	18	155 to –1,088	Caseyville, Tradewater
Mississippian sandstone	94	556 to –2,464	Cypress, Tar Springs
Mississippian carbonate	42	579 to –2,330	Paint Creek, Ste. Genevieve
Devonian shale	30	457 to –1,190	New Albany
Devonian carbonate	6	–62 to –3,831	Boyle, Clear Creek, Jeffersonville
Silurian carbonate	4	377 to –1,798	Laurel/Osgood, Lego
Ordovician sandstone	2	–1,498 to –3,165	Knox–Rose Run, St. Peter
Ordovician carbonate	7	–1,094 to –4,137	Knox–Beekmantown
Cambrian dolomite	18	–951 to –7,605	Knox–Copper Ridge
Cambrian-Precambrian sandstone, crystalline rocks	1	–5,256	Mount Simon, basal sandstone, igneous/metamorphic basement
Appalachian Basin			
Pennsylvanian coal	2	1,480 to 1,200	Elkhorn Nos. 2 and 3 coals
Pennsylvanian sandstone	50	1,550 to –572	Salt sand, Pottsville, Lee
Mississippian sandstone	35	62 to –2,362	Berea, Weir, Maxon, Injun
Mississippian limestone	5	920 to –1,229	Newman, Big Lime
Silurian sandstone	2	–1,327, –1,962	Big Six
Silurian dolomite	17	–393 to –1,981	Corniferous, Lockport
Ordovician sandstone	6	–4,264 to –6,623	Knox–Rose Run, St. Peter
Ordovician dolomite	4	–2,325 to –5,181	Knox–Beekmantown, Wells Creek
Cambrian dolomite	6	–2,680 to –5,573	Knox–Copper Ridge
Cambrian limestone	3	–6,913 to –7,671	Maryville
Cambrian sandstone	1	–4,174	basal sandstone
Cambrian shale	2	–3,938, –6,687	Rogersville, Conasauga
Precambrian crystalline rocks	1	–7,765	igneous-metamorphic basement

In eastern Kentucky, the deepest sample was collected from Precambrian metamorphic-igneous basement rock in the Inland Gas Inland No. 533 well in Boyd County (Table 3.1).

The counties for which water data were analyzed for this report reflect, in large part, an attempt to rank areas in Kentucky considered most prospective for geologic sequestration. For example, the eastern Kentucky counties lie on or near the Big Sandy River, which is an important corridor for present and future coal-fired plants. Similarly, in western Kentucky the analyzed counties include parts of the Green and Ohio River corridors. Data from the 23 counties discussed here represent a first phase of analysis, and future work will broaden the area of investigation. Indeed, a second phase of work has begun, and it will include analysis from counties coinciding with important river corridors along which existing and future coal-fired plants are or will be located.

In each basin, the chemistry data were analyzed to determine the main dissolved constituents by general age and rock-type categories (Table 3.1). The age–rock type categories provide a framework for analyzing temporal and stratigraphic variations in dissolved

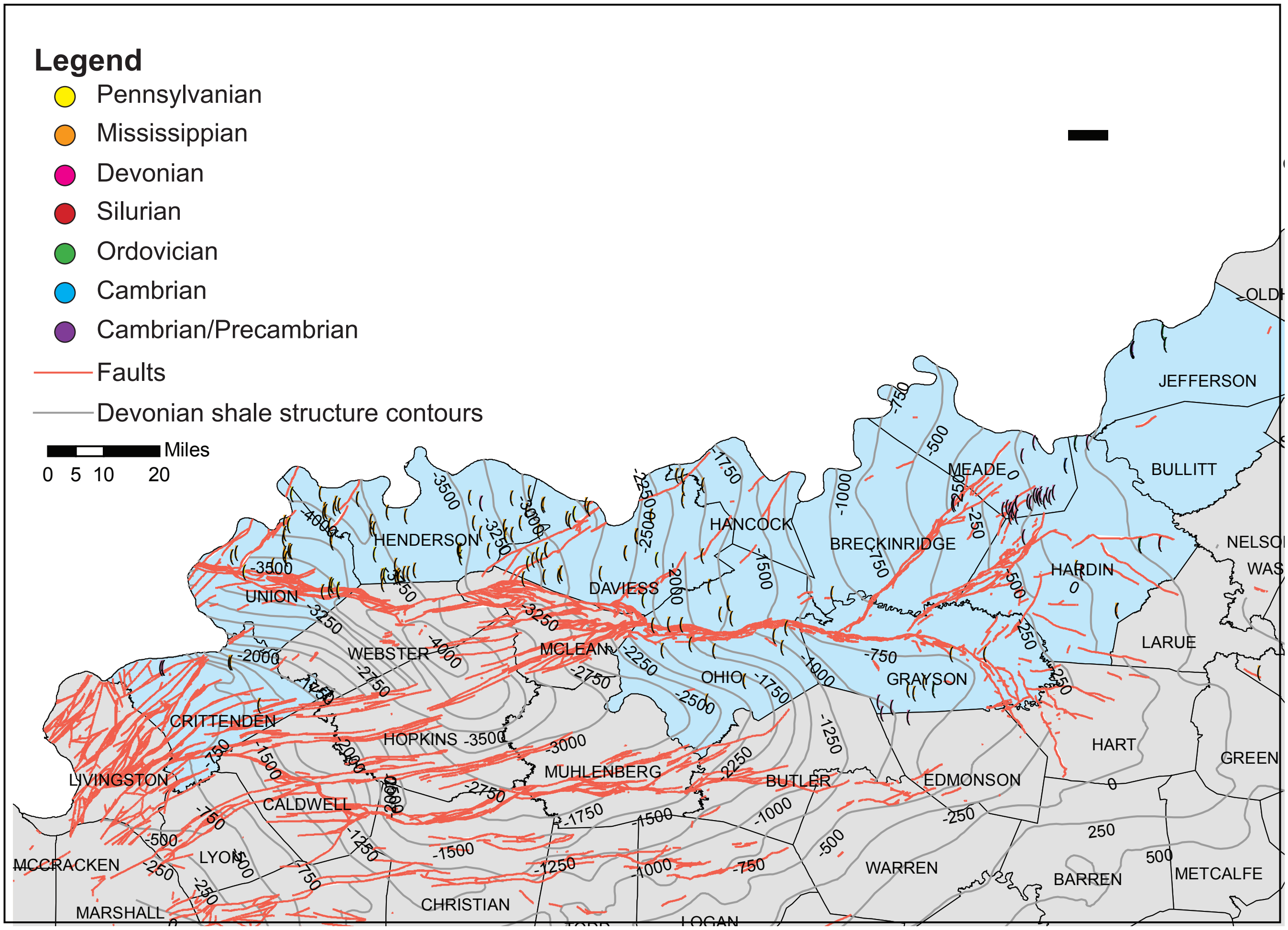

Figure 3.1. Locations and ages of rocks from which water samples were collected in western Kentucky.

constituents and the influence of general rock type on formation-water chemistry. The variation in dissolved constituents, especially Na^+ and Cl^-, also provides a basis for inferring the origin of the formation waters and processes (e.g., evaporation and mixing) that affected their composition.

The chemistry data also provide inputs for calculating the solubility of CO_2 in the formation waters. Solubility was estimated using an equation of state for aqueous solutions containing Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-} from Duan and Sun (2003) and Duan and others (2006). The equation of state covers a wide range of temperature (273 to 533 K or 32 to 571°F), pressure (0 to 2,000 bars or 0 to 29,007 psi), and ionic strength (0 to 4.5 molality of salts) and predicts solubility at two-phase coexistence (vapor-liquid, liquid-liquid). Solubility of CO_2 is calculated by:

$$\ln m_{CO2} = \ln y_{CO2} Ø_{CO2} P - \mu_{CO2}/RT$$
$$-2\lambda_{CO2-Na}(m_{Na} + m_K + 2m_{Ca} + 2m_{Mg})$$
$$-\zeta_{CO2\text{-}Na\text{-}Cl} m_{Cl}(m_{Na} + m_K + m_{Mg} + m_{Ca})$$
$$+ 0.07 m_{SO4}$$

where T is absolute temperature in Kelvin, P is total pressure in bars, R is the universal gas constant (8.314 $JK^{-1}mol^{-1}$), m is the molality of components dissolved in water, y_{CO2} is the mole fraction of CO_2 in the vapor phase, $Ø_{CO2}$ is the fugacity coefficient of CO_2, μCO_2 is the standard chemical potential of CO_2 in liquid phase, λ_{CO2}–Na^+ is the interaction parameter between CO_2 and Na^+ and $\zeta_{CO2-Na+-Cl-}$ is the interaction parameter between CO_2 and Na^+ and Cl^-. Previously, a complex iterative process was needed to solve for the fugacity coefficient, $Ø_{CO2}$; however, Duan and others (2006) provided a noniterative equation to calculate $Ø_{CO2}$ as a function of temperature (T) and pressure (P):

$$Ø_{CO2} = c_1 + (c_2 + c_3T + c_4/T + c_5/(T-150))P$$
$$+ (c_6 + c_7T + c_8/T)P^2$$
$$(c_9 + c_{10}T + c_{11}/T)\ln P + (c_{12} + c_{13}T)/P$$
$$+ c_{14}/T + c_{15}T^2$$

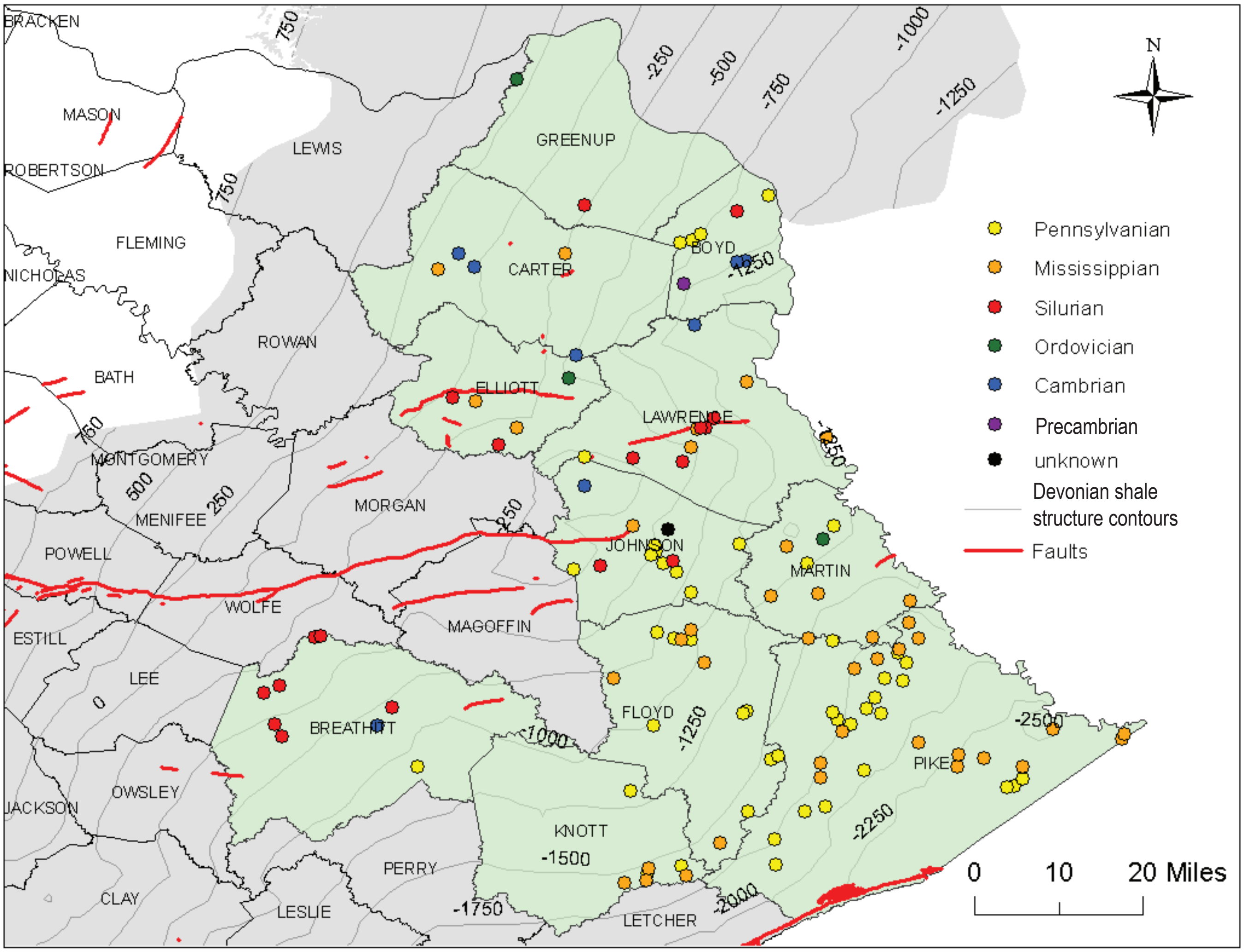

Figure 3.2. Locations and ages of rocks from which water samples were collected in eastern Kentucky.

where T is in Kelvin and P in bars. The parameters c_1, c_2, c_3, … c_{15} are provided in Duan and others (2006) for specific temperature and pressure ranges and were fitted to the values of $Ø_{CO2}$ as calculated from the equation of state from Duan and others (1992).

Reservoir temperature was estimated using the equation:

$$\text{Temperature (°F)} = (0.0235 \times \text{sample depth}) + 54°\text{F}$$

where 0.0235 is the geothermal gradient (°F/ft), sample depth (ft) is the approximate midpoint depth over the interval from which the sample was collected referenced to the ground surface, and 54°F is the average surface temperature in Kentucky. Reservoir pressure, assumed to be near or at hydrostatic pressure, was estimated with the equation:

$$\text{Pressure (psi)} = 0.433 \times \text{sample depth}$$

where 0.433 is the average hydrostatic gradient (psi/ft) and sample depth (ft) is the approximate midpoint depth over the interval from which the sample was collected, referenced to sea level.

Results

Major Element Chemistry

Chloride (Cl^-) is the dominant anion in Appalachian and Illinois Basin samples, with concentrations on the order of 103 to 105 mg/L (Table 3.2). The large standard deviations with Cl^- and other anions and cations for a given age–rock type category results from averaging values for samples that were collected over a wide range of burial conditions. In the Illinois Basin, Cl^- is followed by SO_4^{2-} (102 to 103 mg/L), HCO_3^- (102 to 103 mg/L), Br^- (101 to 102 mg/L), and nearly equal amounts of F^- and I^- (100 to 101 mg/L), in order of decreasing concentration. The sequence, however, Kentucky Geological Survey

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UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WATER ANALYSIS

Ku 107

2GW

Location Newman, Kentucky (23-Q-27)(2,060 FSL-950 FEL) County Daviess
Source Well No. 1 Depth (ft) 1,835-41 Diam (in.).
Cased to (ft) Date drilled 1969 Point of coll.
Owner J. E. Raley, and Elmo Holder
Treatment Use
WBF Auxvases WL Yield
Temp (°C) Appear. when coll.
Collected November 5, 1969 By H. S.
Remarks Red Quadrangle. Field: Birk City, AV zone. Gage: 75 BOPD, 50 BWPD.

	mg/l	me/l		mg/l	me/l
Silica (SiO_2)	72	--	Bicarbonate (HCO_3)	325	5.33
Aluminum (Al)			Carbonate (CO_3)	0	.00
Iron (Fe)	.00	--			
Manganese (Mn)	.26	--	Sulfate (SO_4)	1,270	26.44
			Chloride (Cl)	51,000	1438.71
			Fluoride (F)	5.3	.28
			Bromide (Br)	114	1.43
Calcium (Ca)	2,840	141.72	Iodide (I)	15	.12
Magnesium (Mg)	1,480	121.74	Nitrate (NO_3)		
Sodium (Na)	27,000	1174.50			
Potassium (K)	173	4.42			
Total		1442.38	Total		1472.31

	mg/l		
		Specific conductance (micromhos at 25° C)	105,000
Dissolved solids: Calculated	84,000	pH	7.4
Residue on evaporation at 180°C	93,200	Color	
Hardness as $CaCO_3$	13,200	Density at 20.0°C.	1.062
	12,900		

Lab. No. Col 53840 Field No. Project KENTUCKY WRD - GW BRINE

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Figure 3.3. Example of USGS water data sheet that, along with other data sheets, was the principal source of data for this study.

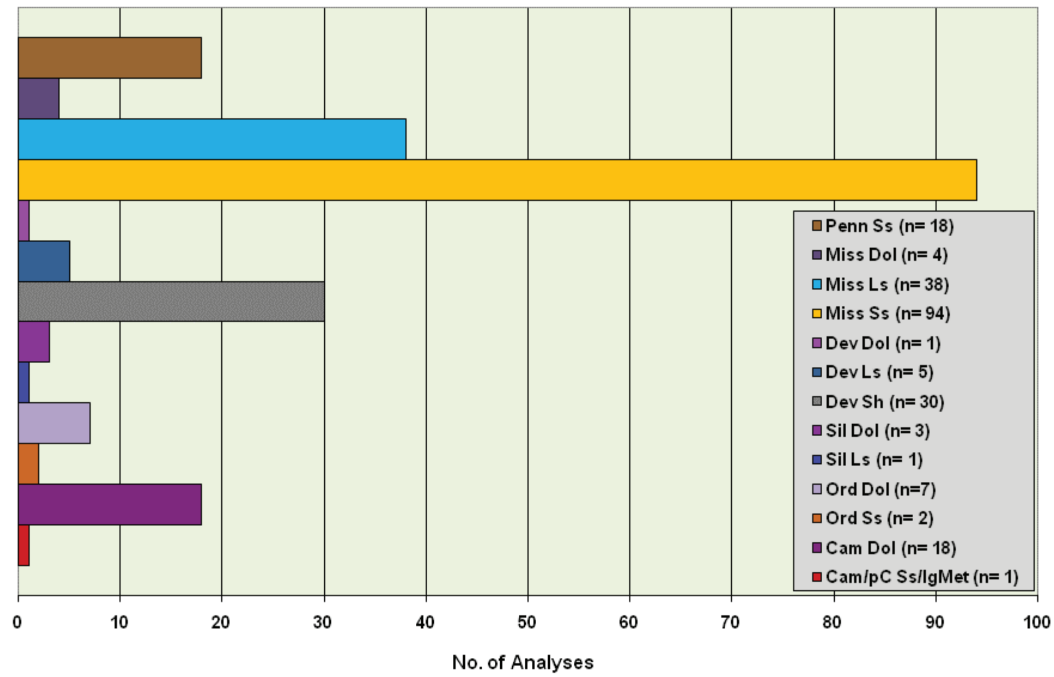

Figure 3.4. Stratigraphic distribution of formation-water data from western Kentucky (Illinois Basin).

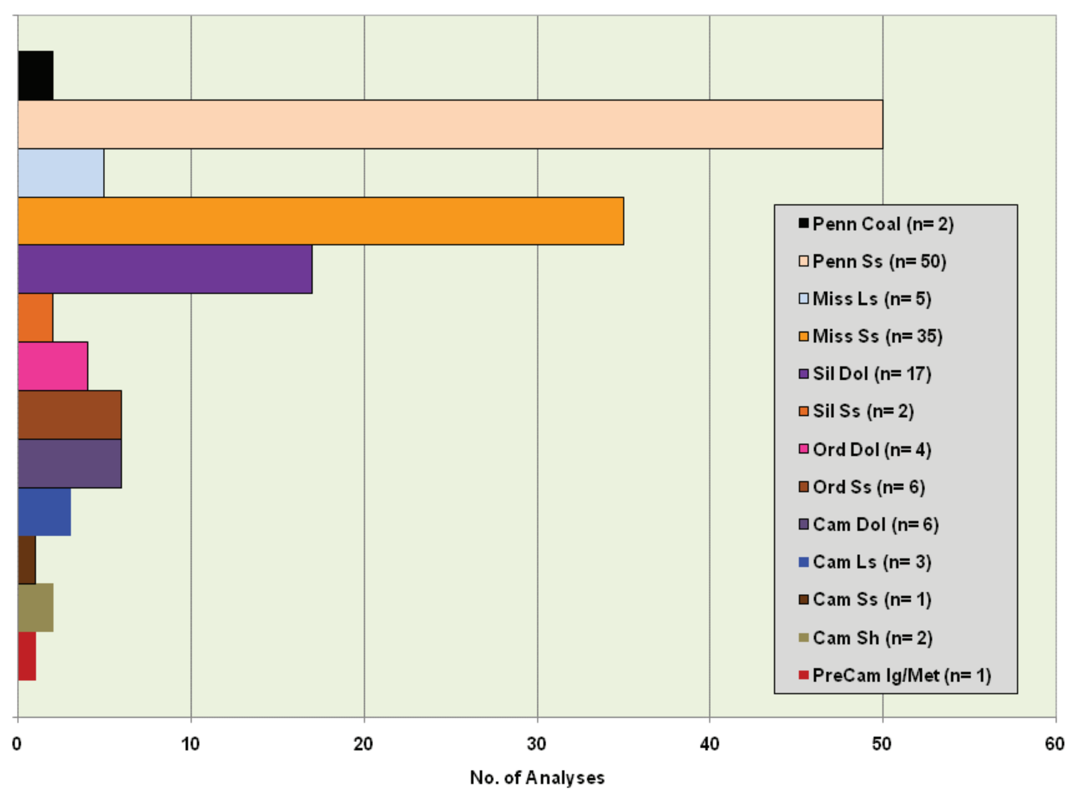

Figure 3.5. Stratigraphic distribution of formation-water data from eastern Kentucky (Appalachian Basin).

Table 3.2. Average (with one standard deviation) formation-water anion concentrations (mg/L). The number of measurements per average is in parentheses. Carbonate means a mixture of limestone and dolostone. Where combined, the first is the dominant rock type.

Age–Rock Type	*Cl⁻*	*SO_4^{-2}*	*HCO_3^{-}*	*Br*	*F*	*I*
Illinois Basin						
Pennsylvanian sandstone	8,475 ± 5,492 (16)	1,614 ± 1,830 (16)	1,099 ± 1,249 (14)	21 ± 10 (10)	2.0 ± 2.4 (8)	1.2 1.5 (10)
Mississippian sandstone	27,735 ± 19,861 (72)	1,152 ± 1,465 (66)	349 ± 318 (64)	77 ± 59 (43)	1.5 ± 1.0 (39)	5.1 ± 3.7 (41)
Mississippian carbonate	40,618 ± 24,631 (36)	1,326 ± 1,007 (34)	229 ± 228 (32)	126 ± 78 (15)	2.9 ± 2.3 (18)	9.8 ± 5.1 (14)
Devonian shale	46,880 ± 16,498 (30)	219 ± 163 (30)	1,190 ± 671 (5)	204 ± 50 (23)	nd	nd
Devonian carbonate	27,605 ± 36,419 (6)	367 ± 233 (5)	340 ± 271 (5)	97 ± 36 (3)	1.6 (1)	1.6 ± 1.0 (3)
Silurian carbonate	25,580 ± 26,016 (4)	811 ± 748 (4)	307 ± 265 (4)	49 ± 62 (3)	1.6 ± 1.5 (3)	1.6 ± 2.6 (3)
Ordovician carbonate sandstone	9,026 ± 4,395 (11)	1,644 ± 751 (10)	274 ± 120 (8)	42 ± 19 (5)	1.8 ± 0.2 (4)	1.6 ± 1.8 (5)
Cambrian dolomite	26,130 ± 33,123 (16)	1,950 ± 1,022 (16)	263 ± 110 (16)	47 ± 26 (6)	1.8 ± 0.4 (13)	0.8 ± 0.7 (6)
Appalachian Basin						
Pennsylvanian sandstone	26.860 ± 28,280 (49)	10 ± 19 (39)	143 ± 150 (41)	202 ± 162 (30)	0.6 ± 0.5 (16)	7.3 ± 3.5 (30)
Mississippian carbonate sandstone	73,131 ± 40,648 (35)	50 ± 108 (29)	34 ± 48 (32)	313 ± 162 (30)	1.5 ± 1.5 (14)	11.1 ± 14 (30)
Silurian carbonate sandstone	116,555 ± 44,966 (19)	432 ± 488 (19)	96 ± 123 (19)	625 ± 572 (19)	4.6 ± 2.3 (11)	17.3 ± 9.9 (19)
Ordovician carbonate sandstone	125,639 ± 33,476 (8)	245 ± 192 (7)	140 ± 94 (7)	689 ± 403 (8)	5.5 ± 2.0 (6)	30.1 ± 9.9 (8)
Cambrian carbonate sandstone	112,064 ± 258 (11)	372 ± 353 (11)	83 ± 50 (11)	627 ± 375 (12)	7.6 ± 1.8 (7)	29.7 ± 16 (11)

does not apply to samples from the New Albany Shale, which have an average HCO_3^- value equal to 1,190 ±671 mg/L and exceed SO_4^{-2} by an order of magnitude. The average HCO_3^- value in the New Albany is the highest recorded in the study.

Samples from the Appalachian Basin, in contrast, have very different anion concentrations, both in terms of relative proportion and absolute value (Table 3.2). After Cl^-, the concentrations of anions, in decreasing order, are Br^- (102 mg/L), SO_4^{2-} (101 to 102 mg/L) or HCO_3^- (101 to 102 mg/L); and I^- concentrations (101 to 102 mg/L) are distinctly higher than F^- (100 to 101 mg/L). When comparing similar-age units and rock types between basins, SO_4^{2-} and HCO_3^- are higher in the Illinois Basin samples and Br^- and I^- are higher in Appalachian Basin samples.

Cations that belong to the alkaline metals (e.g., K+, Na+) and alkaline earth metals (e.g., Ca^{2+}, Mg^{2+}) primarily occur in solution as ionic-bonded compounds with Cl^- (Drever, 1988), and therefore it is appropriate to analyze cation concentrations and distribution as chloride compounds (Hanor, 1994; Worden, 1996). The analysis shows that Na^+ is the dominant cation and has a strong positive correlation with Cl^- (Table 3.3, Fig. 3.6). This observation accords with analyses of formation waters from sedimentary basins around the world (Hanor, 1994). Once in solution, Na^+ tends to be non-reactive with rock-forming minerals, and consequently

Table 3.3. Average (with one standard deviation) formation-water cation concentrations (mg/L). Number of measurements per average is in parentheses. Carbonate means a mixture of limestone and dolostone. Where combined, the first is the dominant rock type.

Age–Rock Type	*Na^+*	*Ca^{2+}*	*Mg^{2+}*	*K^+*
Illinois Basin				
Pennsylvanian sandstone	5,227 ± 2,798 (11)	346 ± 449 (14)	70 ± 71 (14)	26 ± 19 (10)
Mississippian sandstone	16,723 ± 10,583 (63)	1,419 ± 2,138 (64)	512 ± 508 (63)	157 ± 522 (43)
Mississippian carbonate	19,546 ± 13,214 (29)	2,817 ± 4,101 (30)	1,061 ± 729 (30)	112 ± 132 (16)
Devonian shale-carbonate	24,610 ± 8,418 (29)	2,642 ± 1,399 (30)	1,352 ± 541 (30)	478 ± 288 (25)
Silurian carbonate	8,547 ± 10,518 (3)	670 ± 897 (3)	576 ± 815 (3)	32 ± 44 (2)
Ordovician carbonate-sandstone	3,943 ± 2,566 (4)	812 ± 261 (7)	361 ± 110 (6)	133 ± 31 (3)
Cambrian dolomite-sandstone	12,291 ± 13,249 (16)	3,456 ± 5,161 (16)	886 ± 1,177 (16)	206 ± 124 (13)
Appalachian Basin				
Pennsylvanian sandstone	15,396 ± 14,883 (37)	3,529 ± 4,388 (38)	743 ± 852 (37)	197 ± 381 (34)
Mississippian carbonate-sandstone	33,643 ± 17,643 (28)	9,727 ± 5,621 (28)	2,090 ± 1,296 (28)	278 ± 201 (27)
Silurian carbonate-sandstone	45,233 ± 16,168 (17)	18,200 ± 9,423 (17)	4,682 ± 2,913 (17)	1,056 ± 1,022 (17)
Ordovician carbonate-sandstone	42,971 ± 8,143 (6)	29,341 ± 7,028 (5)	4,745 ± 2,140 (5)	2,975 ± 1,348 (6)
Cambrian dolomite-sandstone	40,871 ± 10,004 (7)	21,683 ± 12,808 (7)	3,200 ± 1,773 (7)	2,286 ± 1,244 (7)

its distribution can be used to infer processes such as dilution and evaporation that influence compositional evolution (Hanor, 1994). Most of the samples in this study show a well-defined linear distribution for Na^+ versus Cl^- that intersects the average NaCl composition of seawater (Fig. 3.7). This distribution suggests that most samples in this study have a marine origin.

After Na^+, the concentration of cations, in decreasing order, is Ca^{2+}, Mg^{2+}, and K^+ (Fig. 3.6, Table 3.3); this relative distribution is similar to formation waters in other sedimentary basins (Hanor, 1994). Plots of Ca^{2+}, Mg^{2+}, and K^+ versus Cl^- are similar to plots for Na^+ versus Cl^-, but often the slopes differ significantly. The difference implies that processes in addition to dilution and evaporation have affected water composition. For example, when compared to Na^+ versus Cl^-, plots for Mg^{2+} and K^+ versus Cl^- for Cambrian-Ordovician Knox Group samples from the Appalachian Basin have significantly lower slopes (Fig. 3.8). The slope of Ca^{2+} versus Cl^- for the same group of samples is slightly steeper compared to the slope of Na^{2+} versus Cl^-. Considered jointly, the shallower slope for Mg^{2+} and steeper slope for Ca^{2+} may reflect the process of dolomitization, in which Ca^{2+} is released into and Mg^{2+} taken out of the formation fluid according to the reaction:

$$2CaCO_3 + Mg^{2+} = CaMg(CO_3)_2 + Ca^{2+}.$$

Of the major cations typically measured, K^+ tends to have a distribution most dissimilar to that of Na^{2+}. The dissimilarity results, in large part, from the ease with which K^+, independent of Cl^-, is incorporated into clay minerals (Hem, 1992). A potential example of this is provided in the New Albany Shale, in which

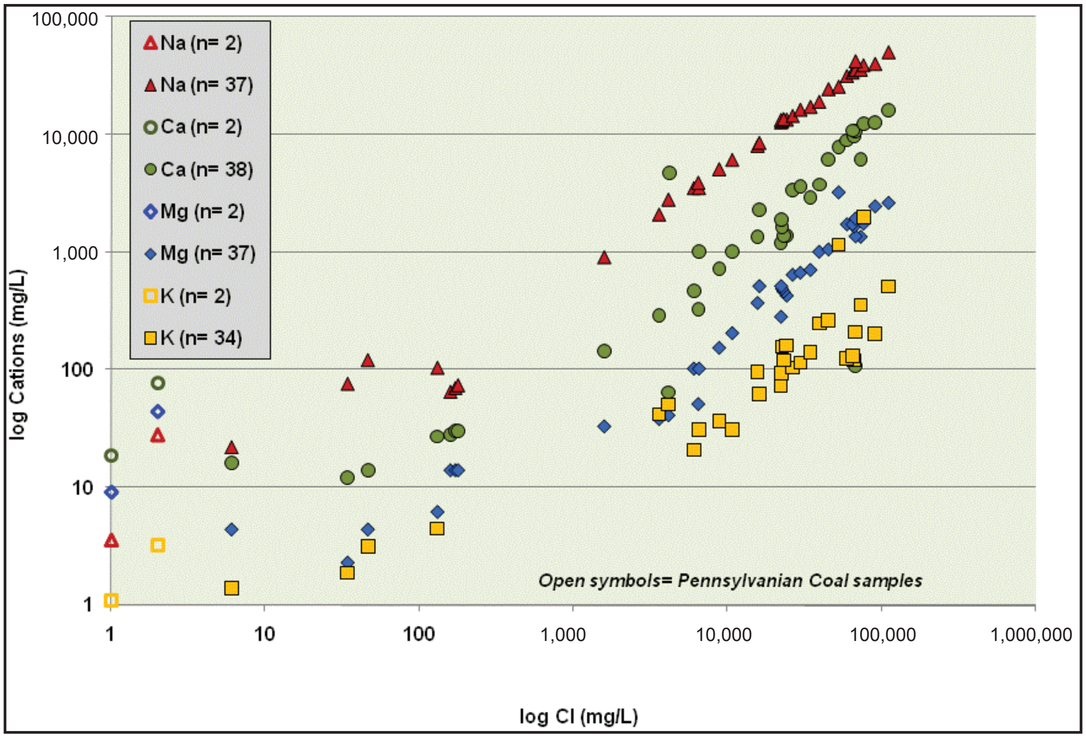

Figure 3.6. Na⁺, Ca⁺², Mg⁺², and K⁺ versus Cl for Pennsylvanian sandstone and coal reservoirs in eastern Kentucky (Appalachian Basin).

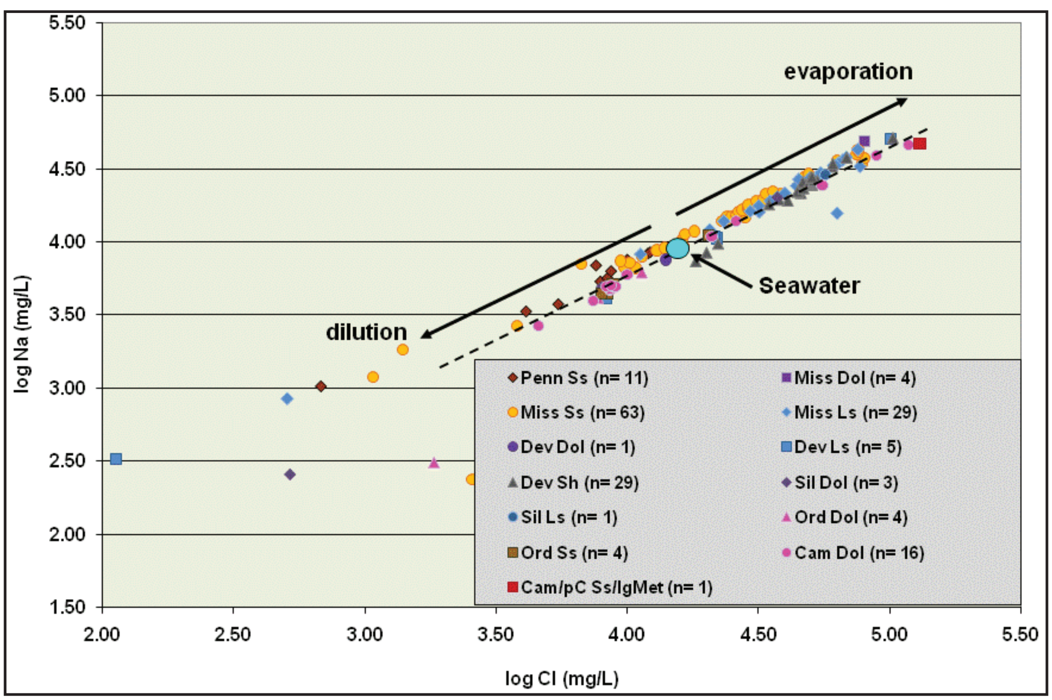

Figure 3.7. Log Na⁺ versus log Cl by age–rock type in western Kentucky (Illinois Basin). Most data fall on or near a trend originating with a seawater composition subsequently altered by evaporation or dilution.

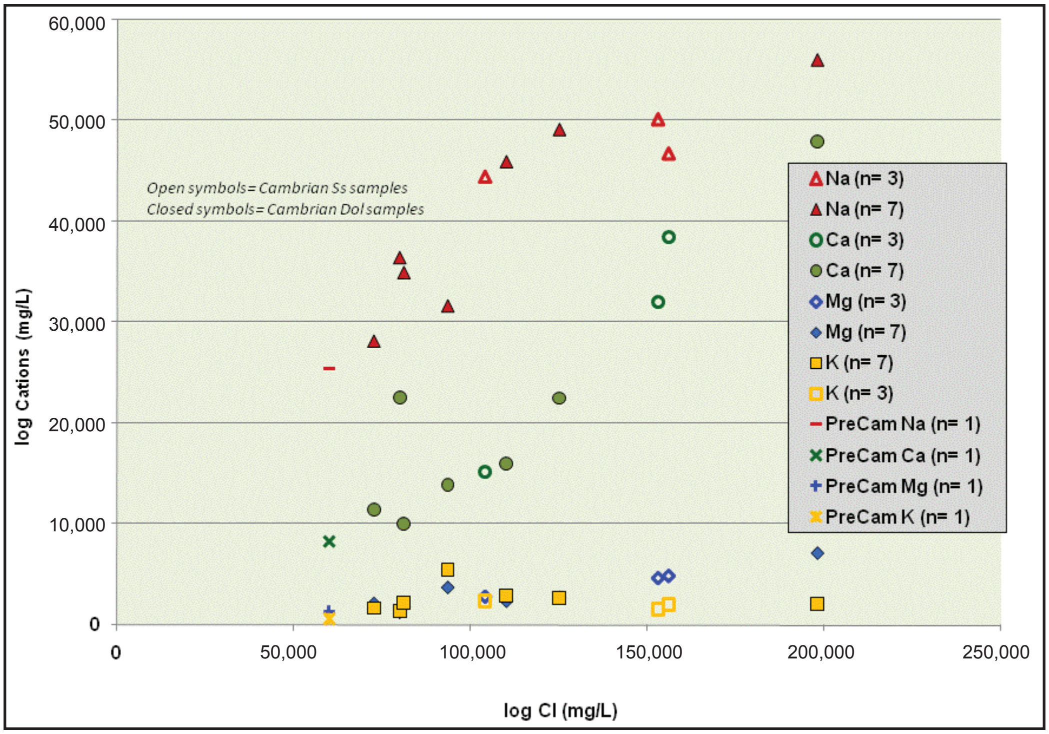

Figure 3.8. Na^+, Ca^{2+}, Mg^{2+}, and K^+ versus Cl^- for Ordovician-Cambrian sandstone and dolomite samples and a Precambrian igneous/metamorphic sample from eastern Kentucky (Appalachian Basin).

concentrations of K^+, Mg^{2+}, and Ca^{2+} vary significantly, whereas the concentration of Cl^- does not (Fig. 3.9).

Total Dissolved Solids

Total dissolved solids equals the total amount of solids (mg/L) remaining when a water sample is evaporated to dryness (Drever, 1988). This residual mass, called the residual TDS, represents the sum of all dissolved constituents. In addition to being measured through evaporation, TDS may also be calculated. The term “TDS” is equivalent to the term “salinity,” and they are used interchangeably here.

When plotted versus depth, TDS values in the Appalachian Basin group into two populations (Fig. 3.10). A shallow population from 1,480 to –1,981 ft includes water samples from Pennsylvanian, Mississippian, and Silurian rocks. The shallow population is a fairly well-defined linear trend in which salinity increases approximately 230 mg/L per ft. Just below this shallow population is a small group of samples at approximately –2,200 ft that have salinities (approximately 25,000 to 150,000 mg/L) lower than what would be predicted by the trend of the shallow population. The group at –2,200 ft includes five samples from the Mississippian Berea Sandstone in Pike County and a sample from the Ordovician Wells Creek Dolomite in Greenup County. Geologic analysis shows that none of the wells are near faults, which would appear to preclude the possibility of meteoric water (i.e., rainwater) infiltration along a fault and into the reservoirs. Alternatively, the lower than expected salinities could result from field or analytical error but the occurrence of low salinity in five wells, all from the Berea Sandstone, suggests the possibility of an underlying geologic reason, at least for these samples.

A second population is defined by deeper TDS data distributed from –4,100 to –7,900 ft and includes samples from Ordovician, Cambrian, and Precambrian rocks (Fig. 3.10). Salinities for the deeper samples range from approximately 100,000 to 320,000 mg/L. The deeper data do not show a defined trend of salinity with depth, and indeed the deepest sample from the Precambrian is the most dilute in the deeper population. Over half of the deeper samples (53 percent) were collected from wells operated by Inland Gas Co. in Boyd County.

TDS values for samples from the Illinois Basin also define two populations, but the distribution of salinity versus depth differs from that for the Appalachian Basin (Fig. 3.11). Again, a shallow population is largely defined by data from 579 to –2,464 ft that includes Pennsylvanian, Mississippian, Devonian, and

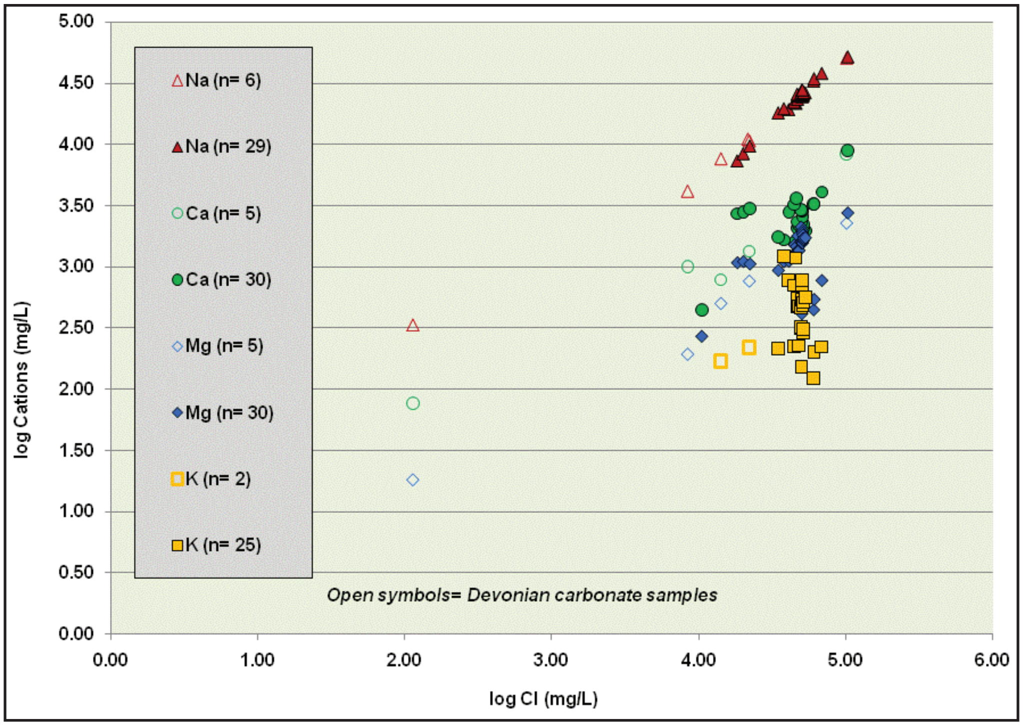

Figure 3.9. Na^+, Ca^{2+}, Mg^{2+}, and K^+ versus Cl^- for Devonian New Albany Shale samples from western Kentucky (Illinois Basin).

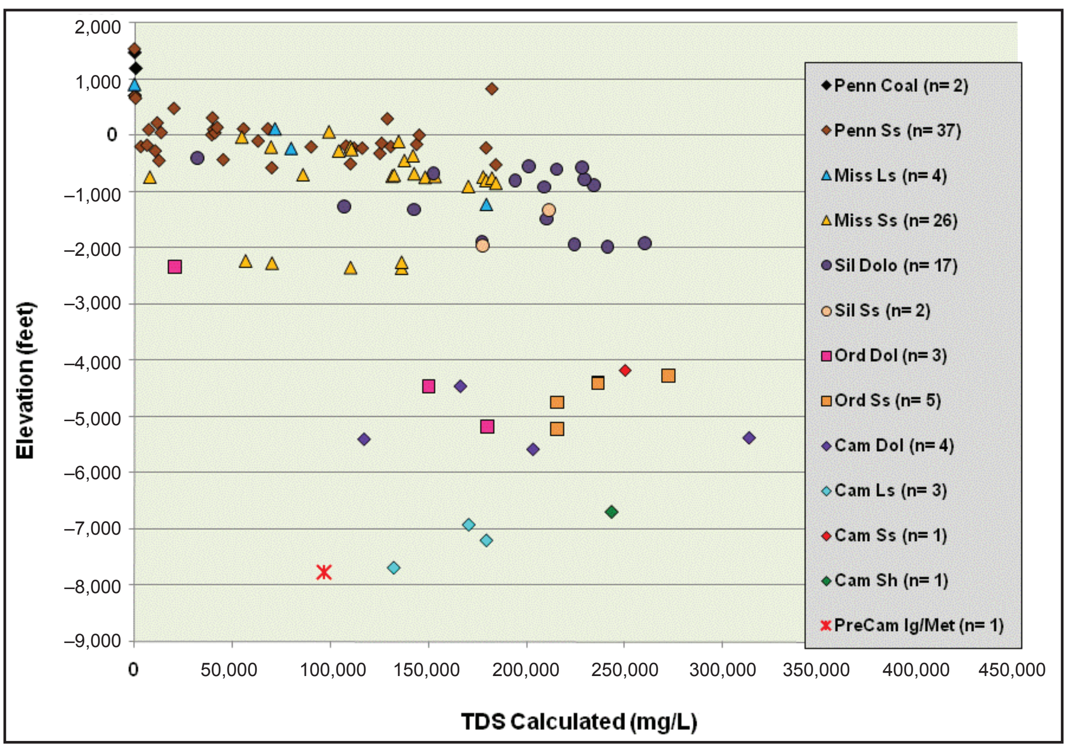

Figure 3.10. Salinity (TDS, mg/L) versus elevation (ft) by age–rock type for formation waters in eastern Kentucky (Appalachian Basin).

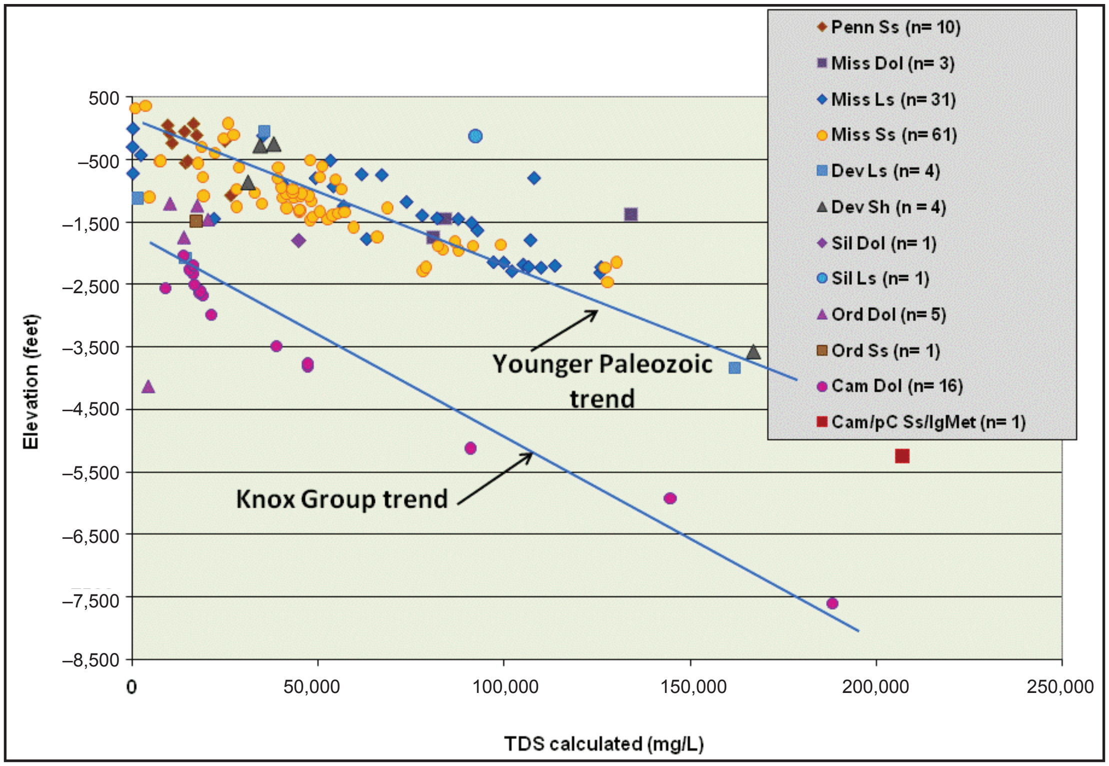

Figure 3.11. Salinity (TDS, mg/L) versus elevation (ft) by age–rock type for formation waters in western Kentucky (Illinois Basin).

Silurian samples. When projected deeper, the trend also includes Devonian samples at approximately –3,800 ft and a Precambrian sample at –5,256 ft. The trend through these samples defines an increase in salinity of approximately 80 mg/L per ft.

The second population of data is defined by samples from approximately –1,500 to –7,600 ft, most of which come from the Cambrian Knox Group (Fig. 3.11). The three deepest Knox samples (–5,125, –5,927, and –7,605 ft) were collected from the Shell M.D. Davis No. 1 well in Crittenden County, and most of the remaining Knox samples at –3,700 ft and shallower were collected from the DuPont WAD No. 1 and No. 2 wells in Jefferson County. Ordovician samples from the Wells Creek Dolomite and St. Peter Sandstone were also analyzed, and these samples plot near the intersection with the shallow data population. Consequently, it is difficult to determine if these samples should group with the shallow or Knox data. A best-fit line through the Knox samples defines an increase in salinity of approximately 60 mg/L per ft.

CO_2 Solubility

As illustrated in the equation of state from Duan and others (2006), the solubility of CO_2 in formation waters is a function of temperature and pressure, and the quantity and type of dissolved constituents and their interactions. Along with estimating the magnitude of dissolution, the relative strengths of these influences can be assessed by discriminating CO_2 solubility against these factors. One critical limitation is that the Duan and others (2006) equation of state is limited to samples having TDS values less than 200,000 mg/L. The limitation precluded us from calculating solubility in more-saline formation fluids that occurred in many of the age–rock type categories (Table 3.4). For example, 72 percent of Silurian and 56 percent of Ordovician samples from the Appalachian Basin had salinities too high to calculate CO_2 solubility. A further undesirable consequence of the salinity limitation is that it metamorphic-culled the high-salinity data, which, in turn, resulted in CO_2 solubility averages being higher for age–rock unit categories having many high-salinity samples. Other factors (e.g., pressure, temperature) being equal, however, the equation of state qualitatively predicts that more-saline samples will have lower CO_2 solubility compared to lower-salinity samples in the same age–rock type category.

In the Illinois Basin, CO_2 solubility plotted against TDS shows two sample population distributions, likely

Table 3.4. Average (with one standard deviation) CO_2 solubility in formation waters and the ranges of temperature and pressure over which solubilities were calculated. Where combined, the first is the dominant rock type. Number of analyzed samples is in parentheses after solubility averages with standard deviations.

Age–Rock Type	*Temperature (°C)*	*Pressure (bars)*	*Solubility Averages*
Illinois Basin			
Pennsylvanian sandstone	18–23	1–32	0.242 ± 0.229 (11)
Mississippian sandstone	15–51	1–73	0.536 ± 0.205 (66)
Mississippian limestone/ dolomite	16–49	1–68	0.520 ± 0.187 (6)
Devonian shale	25–67	8–106	0.392 ± 0.195 (5)
Devonian dolomite/ limestone	20–70	2–114	0.465 ± 0.387 (5)
Silurian dolomite/ limestone	20–43	1–53	0.239 ± 0.347 (4)
Ordovician sandstone	39, 65	44, 94	0.822 ± 0.024 (2)
Ordovician dolomite	36–73	32–123	0.806 ± 0.123 (5)
Cambrian dolomite	47–118	61–226	0.859 ± 0.090 (16)
Appalachian Basin			
Pennsylvanian sandstone/ coal	14–42	1–25	0.126 ± 0.141 (39)
Mississippian sandstone*	23–68	1–70	0.261± 0.172 (27)
Mississippian limestone	16–41	1–36	0.168 ± 0.137 (5)
Silurian dolomite/ sandstone*	31–48	12–58	0.369 ± 0.099 (7)
Ordovician dolomite/ sandstone*	58–109	69–197	0.646 ± 0.126 (4)
Cambrian limestone/ dolomite*	83–125	108–253	0.624 ± 0.082 (5)
Precambrian igneous/ metamorphic	126	230	0.824 (1)

*Samples with salinity greater than 200,000 mg/L and beyond the range of the Duan and others (2006) equation of state.

reflecting different solubility behavior (Fig. 3.14). For samples having TDS values greater than 50,000 mg/L, the data show a well-defined trend of decreasing CO_2 solubility with increasing TDS. The solubility of CO_2 decreases from approximately 0.75 to 0.55 mol/kg over the salinity range of 50,000 to 165,000 mg/L. The data in this region consist primarily of water samples from Mississippian limestone and sandstone reservoirs. When projected to lower-salinity and higher-CO_2 solubility values, the trend plots near Ordovician and Cambrian samples, many of which are from the Knox Group.

Other samples with TDS values less than 50,000 mg/L, in contrast, do not show a systematic variation in solubility with TDS, and the solubility values span a larger range from less than 0.1 to 0.75 mol/kg (Fig. 3.14). The lower-TDS values include samples primarily from Pennsylvanian and Mississippian sandstone reservoirs. The absence of a correlation in the lower-salinity regions suggests that other factors influence solubility. When CO_2 solubility is plotted against depth, which serves as a proxy for the effects of temperature and pressure, data from the lower-salinity Pennsylvanian and Mississippian reservoirs show a well-defined positive correlation (Fig. 3.15). Solubility increases with depth to approximately 2,000 ft, below which the data split into two populations. The lower population includes samples from Mississippian sand-

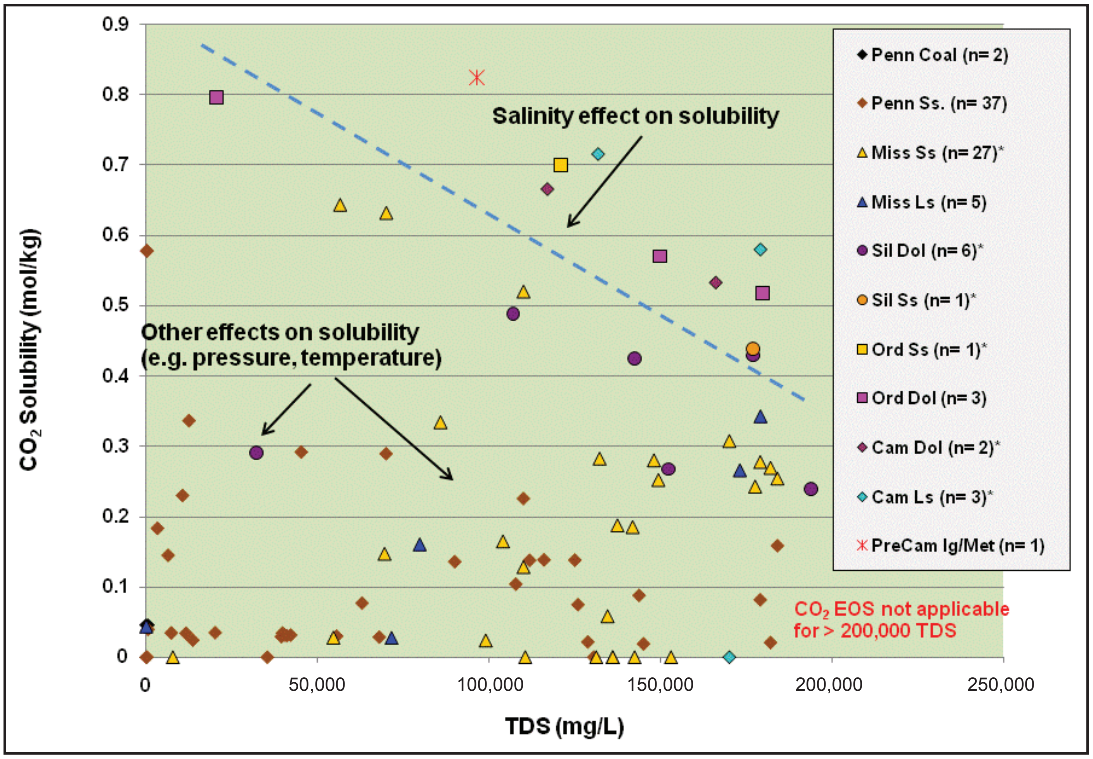

Figure 3.12. Salinity (TDS, mg/L) versus CO_2 solubility (mol/kg H_2O) by age–rock type category for samples in eastern Kentucky (Appalachian Basin).

stone and limestone reservoirs, and it shows a maximum for CO_2 solubility (approximately 0.7 mol/kg) at approximately 1,500 ft, below which solubility decreases. The second population consists of samples primarily from Cambrian dolomite (Knox Group) reservoirs and a smaller number from Ordovician sandstone (St. Peter) reservoirs. The second population shows increasing solubility to a depth of approximately 3,000 ft (solubility maximum of approximately 0.9 mol/kg), below which values decrease.

Similar to samples from the Illinois Basin, Appalachian Basin samples broadly define two regions of different CO_2 solubility behavior when plotted against salinity (Fig. 3.12). A group of higher-CO_2-solubility samples shows a moderately well-developed trend of increasing solubility (approximately 0.4 to 0.8 mol/kg) coincident with decreasing salinity (approximately 175,000 to 25,000 mg/L). This trend consists primarily of Precambrian, Cambrian, and Ordovician samples as well as some samples from Mississippian sandstone and Silurian dolostone reservoirs.

The majority of samples illustrated in Figure 3.12, however, show no systematic variation between CO_2 solubility and salinity. These samples, which come mostly from Pennsylvanian and Mississippian sandstone reservoirs, span a large range of salinity values (129 to 194,000 mg/L), and CO_2 solubility values are less than 0.32 mol/kg. Similar to the Illinois Basin samples, most of the Appalachian Basin Pennsylvanian and Mississippian samples come from relatively shallow depth (less than 2,500 ft), and when depth is plotted against CO_2 solubility, show a well-developed positive correlation (Fig. 3.13). In the same analysis, a second positive trend is defined by the Precambrian, Cambrian, and Ordovician samples.

Discussion

As stated in the "Introduction," the analysis of formation-water chemistry is an important part of assessing an area or basin for geologic carbon storage because it can provide information on potential cross-formation flow between aquifers and the presence of seals that subdivide basin strata into hydrogeologic compartments. When analyzed versus depth, salinity data in eastern and western Kentucky show evidence of a sealing interval.

Formation waters in Cambrian and Ordovician rocks are less saline than would be predicted by the shallow salinity gradients. With other factors such as pressure and temperature being constant, the solubility

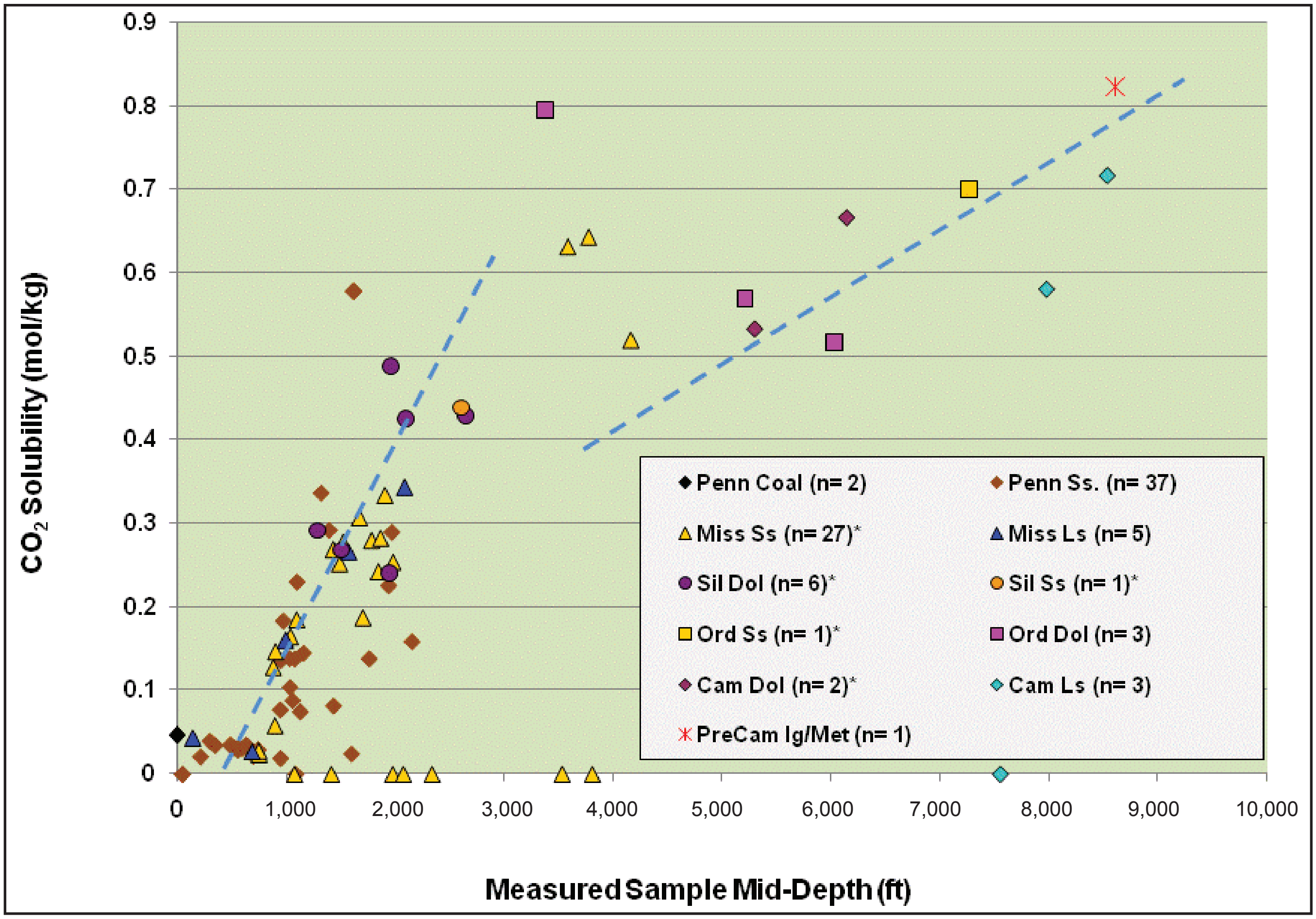

Figure 3.13. Measured depth (ft) versus CO_2 solubility (mol/kg H_2O) by age–rock type category for samples in eastern Kentucky (Appalachian Basin).

of CO_2 in water decreases with increasing salinity (Enick and Klara, 1990). This well-documented relationship thus suggests that more CO_2 could be dissolved into formation waters of Cambrian and Ordovician strata than would be predicted by the shallow salinity-solubility relations. The suggestion is supported by the CO_2 solubility calculations using the Duan and others (2006) equation of state, which show that the highest CO_2 solubilities in this study (approximately 0.65 to 0.86 mol/kg H_2O) are in samples from Ordovician and Cambrian rocks (Table 3.4, Figs. 3.12, 3.14).

The dissolution of CO_2 into formation water, or solubility trapping, is represented by the following reactions:

$$CO_2(g) + H_2O \leftrightarrow H_2CO_3$$
$$H_2CO_3 \leftrightarrow H^+ + HCO_3^-$$
$$HCO_3^- \leftrightarrow H^+ + CO_3^{-2}.$$

The main benefit of solubility trapping is that once CO_2 is dissolved, it no longer exists as a separate phase, be it gas or supercritical fluid, thereby removing the buoyancy forces that would cause it to migrate upward. Reservoir simulations suggest that, over tens of years, up to 30 percent of the injected CO_2 could dissolve in the formation water (Doughty and others, 2001). On a basin scale and over a longer period, modeling suggests that all injected CO_2 could dissolve into the formation water (McPherson and Cole, 2000). The carbonate species (e.g., HCO_3^-, CO_3^{-2}) that evolve from the dissociation of carbonic acid (H_2CO_3) in the above series of reactions also become available for incorporation into minerals such as calcite ($CaCO_3$) and magnesite ($MgCO_3$) through a process called mineral trapping. Mineral trapping is considered the most stable form of geologic storage, but it occurs over longer periods, on the order of thousands of years (Gunter and others, 1993).

Further enhancing the potential for storage in the Cambrian and Ordovician reservoirs is depth, which in

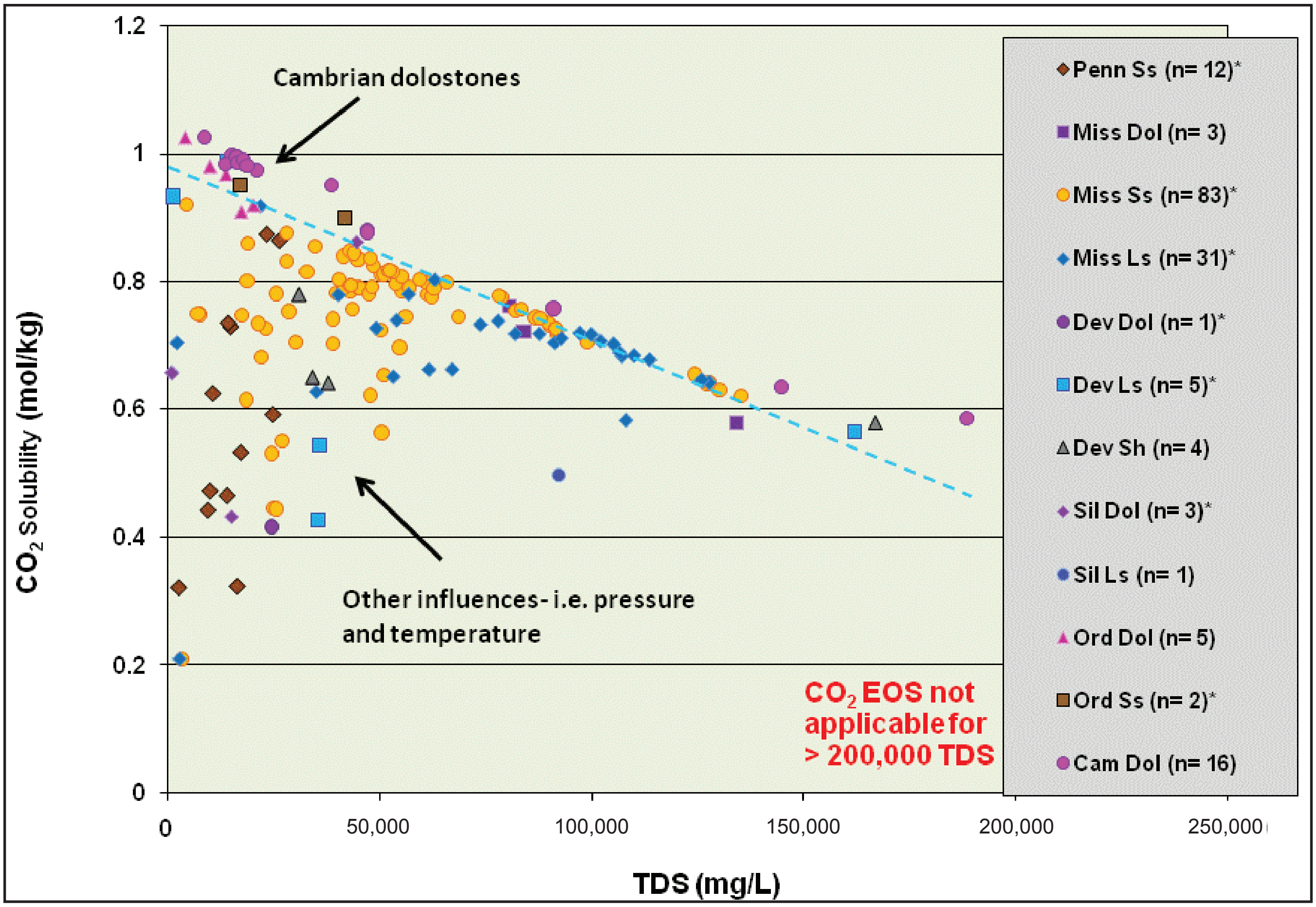

Figure 3.14. Salinity (TDS, mg/L) versus CO_2 solubility (mol/kg H_2O) by age–rock type category for samples in western Kentucky (Illinois Basin).

most cases is greater than the 2,500-ft threshold considered necessary to have supercritical CO_2 in the reservoir. In the Illinois Basin, samples from Cambrian and Ordovician reservoirs show increasing CO_2 solubility that reaches a maximum at about 3,000 ft and then decreases (Fig. 3.15). The subsequent decrease possibly reflects the interplay between temperature, pressure, and salinity in which increasing temperature results in a net decrease in CO_2 solubility. Cambrian and Ordovician samples in the Appalachian Basin, in contrast, show a continuous increase in solubility with depth (Fig. 3.13). The reason for the difference in solubility behavior with depth between basins is not clear and demonstrates the need to perform sensitivity studies to isolate the magnitude of influence of temperature, pressure, and salinity on CO_2 solubility.

Summary

This report is one of the first studies of formation-water chemistry in the context of geologic carbon storage in Kentucky. The water-chemistry data include samples from most Paleozoic reservoirs in the Illinois Basin of western Kentucky and the Appalachian Basin of eastern Kentucky. Important findings from this study are:

1. Formation waters in both basins consist primarily of Na^+ and Cl^-. The distribution of these and other species (e.g., Ca^{2+}, Mg^{2+}, K^+) suggests that the formation waters were derived from seawater and subsequently altered by evaporation, dilution, and water-rock interaction.
2. Salinity versus depth trends show the likely presence of an aerially extensive seal interval in Upper Ordovician rocks that separates Pennsylvanian, Mississippian, Devonian, and Silurian strata from Ordovician and Cambrian strata into broad hydrogeologic compartments. The interval would represent a primary seal for possible CO_2 storage res-

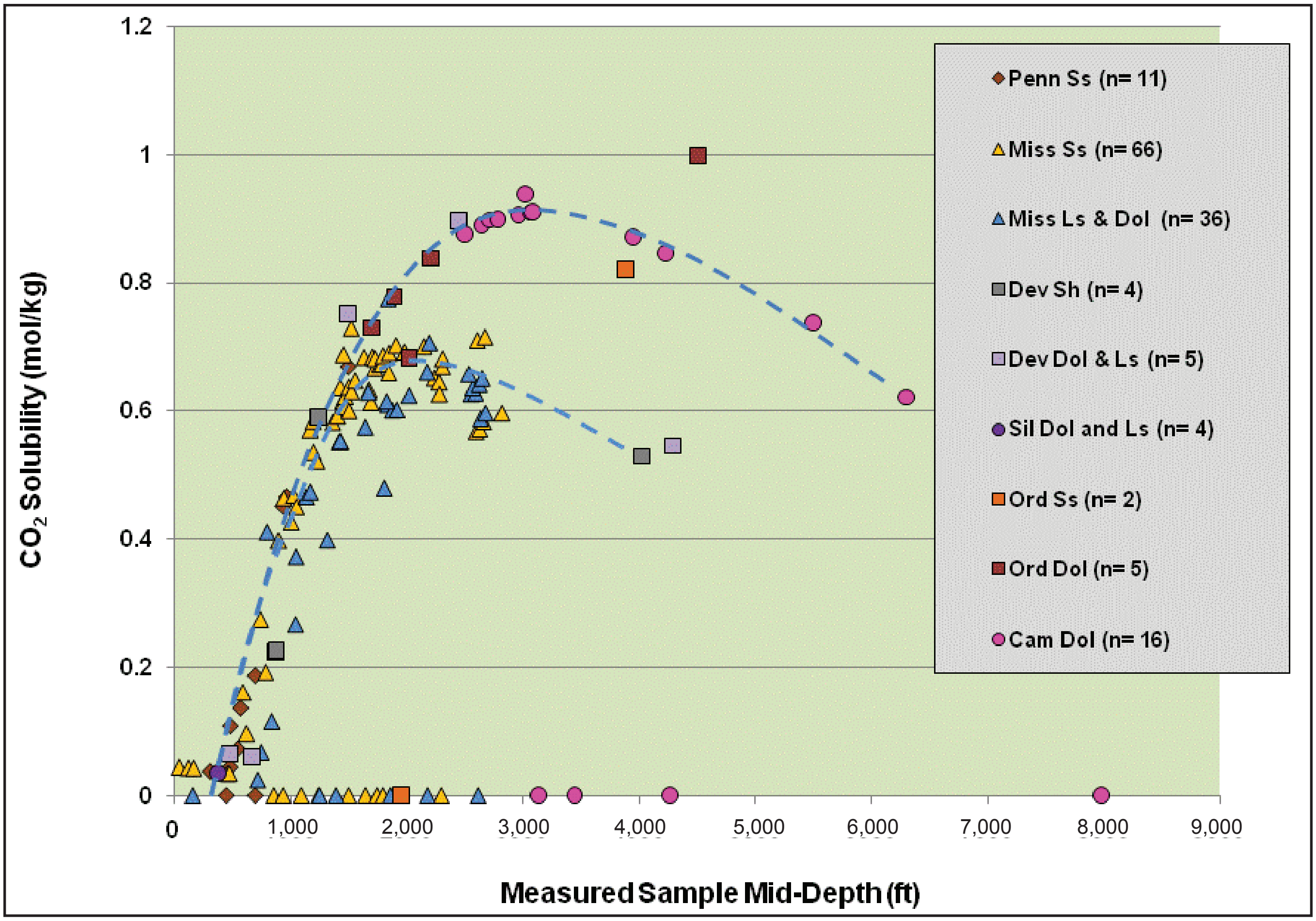

Figure 3.15. Measured depth (ft) versus CO_2 solubility (mol/kg H_2O) by age–rock type category for samples in western Kentucky (Illinois Basin).

ervoirs in the Cambrian-Ordovician Knox Group.

3. Though widely varying, measured salinity values (approximately 4,000 to 313,000 mg/L) in Cambrian and Ordovician reservoirs are often significantly less than what is predicted by salinity-versus-depth trends from shallower Pennsylvanian, Mississippian, Devonian, and Silurian samples. When analyzed with an equation of state for aqueous solutions containing Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-}, the decreased salinity results in higher CO_2 solubilities (approximately 0.65 to 0.86 mol/kg H_2O) and hence more potential for solubility trapping in Cambrian and Ordovician reservoirs.

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Chapter 4: Geologic Carbon Storage (Sequestration) Potential in Kentucky

Stephen F. Greb and Michael P. Solis

Introduction

This section summarizes the regional geologic structures and rock units that are likely to be important for carbon storage in Kentucky. Information is provided for each unit's carbon storage potential or confining characteristics. Cross sections along Kentucky's major river corridors illustrate the depths of potential carbon storage units and lateral changes in subsurface geology. Major rivers were chosen because these are where most of Kentucky's existing large-scale electric utilities are located, and because of water requirements, are the likely sites for future power plants, and large, carbon-producing industrial facilities, including coal-to-liquids plants. A glossary of technical terms is provided in Appendix B.

Geologic Structures

The distribution of rock strata at the surface and in the subsurface in Kentucky is strongly influenced by regional and local structural features. Examples of regional structures are broad basins in which strata are downwarped to form depressions that acted as sediment repositories. Understanding the position of these features helps explain the regional changes in bed dip and depth to various strata that could be used for future carbon storage. Examples of local structural features are faults. Understanding the position of faults and documenting the type and magnitude of offset of strata by faults is important for any type of CO_2 storage project, because the faults could be pathways for leakage. Conversely, faults can also form structural traps and act as seals for potential storage reservoirs. Information about faults, including relative offset of surface and near-surface strata, can be found on 7.5-minute geologic quadrangle maps published by the U.S. Geological Survey and available through the Kentucky Geological Survey. Offset of deeper strata can be determined by analyzing subsurface oil and gas logs and seismic analyses. The relative amount of offset and changes in rock-unit thickness across some of Kentucky's faults can be seen in the cross sections generated for this report.

Major Basins and Grabens

Basins and Arches. Strata in much of eastern Kentucky are part of the Appalachian Basin, an elongate downwarping west of and parallel to the Appalachian Mountains (Fig. 4.1). Strata in western Kentucky are part of the Illinois (also called Eastern Interior) Basin, a semicircular downwarping centered in southern Illinois. The two basins are separated by the Cincinnati Arch, a broad upwarping that extends from Tennessee to southern Ohio. Between the Cincinnati Arch and laterally adjacent basins, Middle Ordovician through Pennsylvanian strata transition from shallow and thinner on the arch to thicker and deeper in the basins. The change is evident in the structural maps shown in the "Rock Unit Summary" section of this chapter. Strata in far western Kentucky are in the northeastern Mississippi Embayment (see, for example, McDowell, 1986b). The embayment is delineated by the surface exposure of Cretaceous and Tertiary Coastal Plain strata and continues south to the Gulf Coastal Plain. The deepest part of the Mississippi Embayment, called the structural axis, in Kentucky coincides with the Mississippi River Valley (Olive, 1980). The embayment was established in the latest Cretaceous, when sediment was deposited above a broad unconformity between tilted and eroded Paleozoic strata and overlying Late Cretaceous strata (Olive, 1980; McDowell, 1986a, b; Schwalb, 1986).

Cambrian Grabens. Subsidence in the Illinois and Appalachian Basins was preceded (or initiated) in two deep structural grabens in Kentucky (Fig. 4.2). Grabens are downdropped structural troughs bounded sharply by normal faults. The Rough Creek Graben of western Kentucky is a Cambrian failed rift in the southern part of the Illinois Basin (Soderberg and Keller, 1981; Keller and others, 1982). During the Cambrian Period, this part of Kentucky tried to split apart, and filled with a great thickness of Cambrian sediments. The graben is a branch of the Reelfoot Rift, a larger structure, which is situated beneath the Mississippi Embayment (Fig. 4.2). The Rough Creek Fault System forms the northern boundary of the Rough Creek Graben. The Pennyrile Fault System and a subparallel set of unnamed faults south of the Pennyrile system delineate the southern boundary (McGuire and Howell, 1963; Harris, 1994; Noger and Drahovzal, 2005).

The Rome Trough of eastern Kentucky, which extends into West Virginia and Pennsylvania, represents a Cambrian rift beneath the Appalachian Basin (McGuire

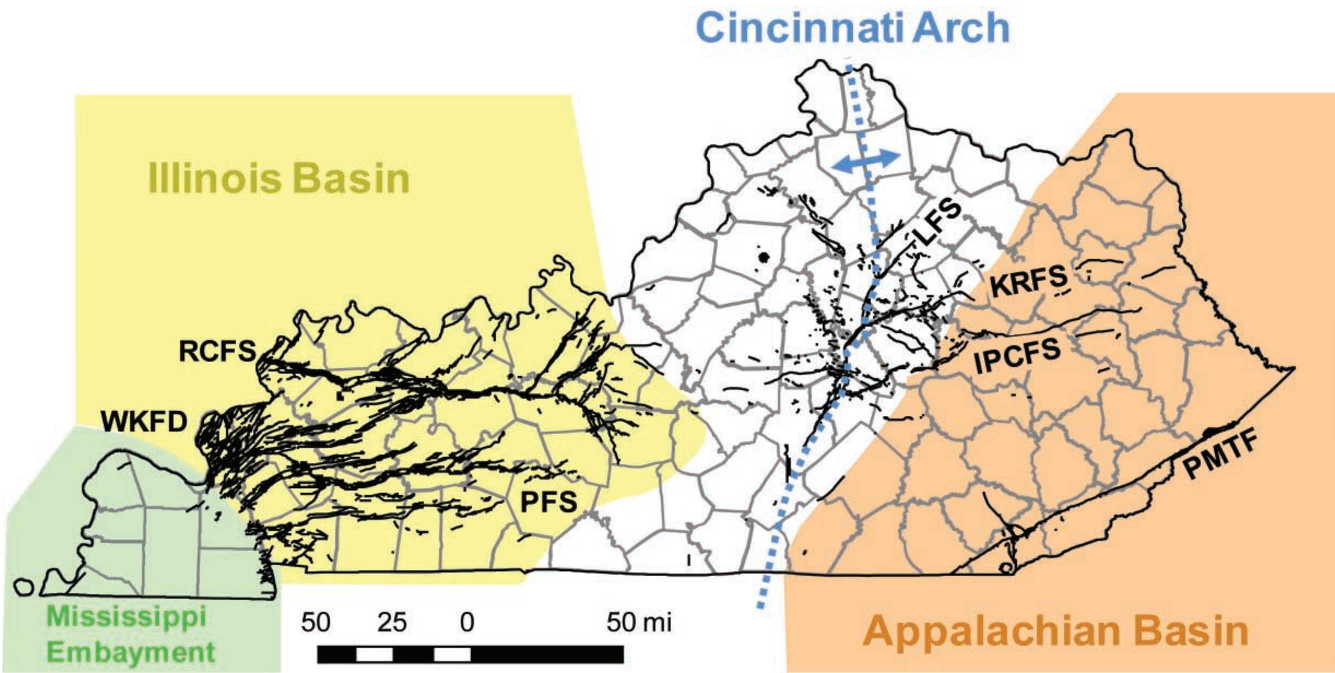

Figure 4.1. The Cincinnati Arch (dotted line) is a broad upwarping (anticline) that separates the Illinois and Appalachian Basins. The basin margins as drawn here coincide approximately with the surface exposure of the top of the Mississippian St. Louis Limestone. IPCFS = Irvine–Paint Creek Fault System. KRFS = Kentucky River Fault System. LFS = Lexington Fault System. PFS = Pennyrile Fault System. PMTF = Pine Mountain Thrust Fault. RCFS = Rough Creek Fault System. WKFD = Western Kentucky Fluorspar District faults.

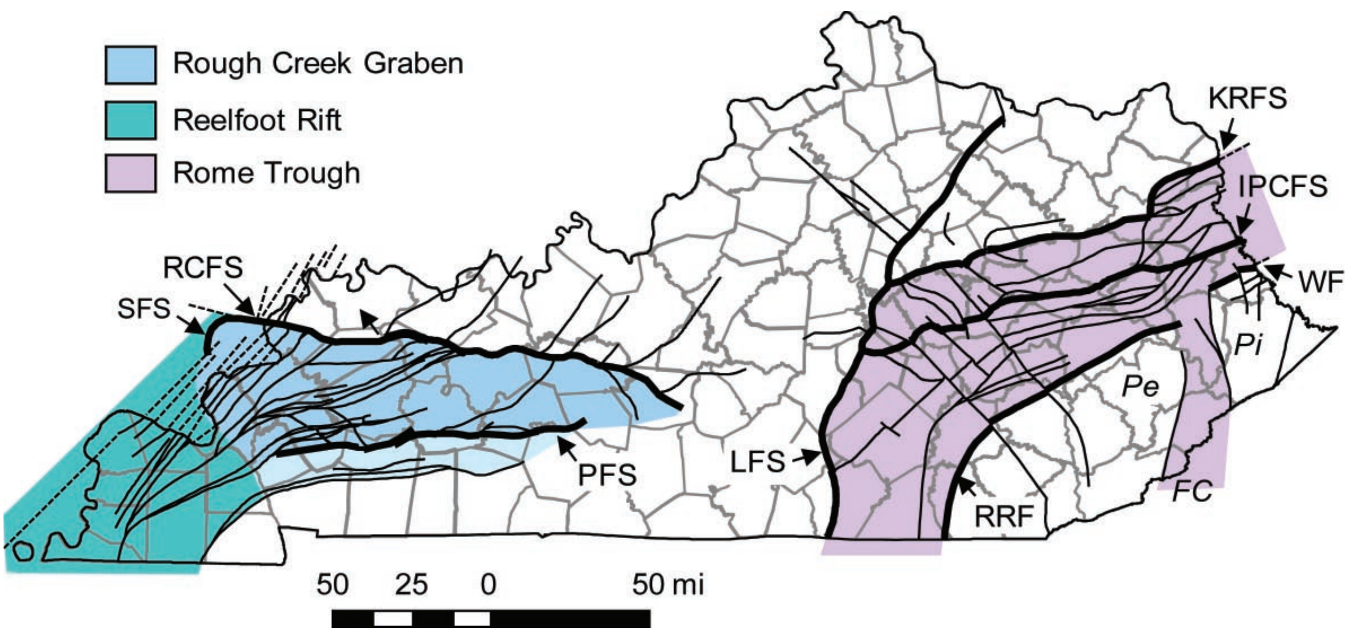

Figure 4.2. Basement faults identified from seismic investigations in Kentucky, and deep Precambrian–Early Cambrian grabens. FC = Floyd County Channel. IPCFS = Irvine–Paint Creek Fault System. KRFS = Kentucky River Fault System. LFS = Lexington Fault System. Pe = Perry County Uplift. PFS = Pennyrile Fault System. Pi = Pike County Uplift. RCFS = Rough Creek Fault System. RRF = Rockcastle River Fault. SFS = Shawneetown Fault System. WKFD = Western Kentucky Fluorspar District Faults. WF = Warfield Fault.

and Howell, 1963; Ammerman and Keller, 1979). The trough is bounded on the north by the Kentucky River Fault System, which has surface expression along part of its length (Fig. 4.2). The southern boundary is the Rockcastle River–Warfield Fault, which is not exposed at the surface. Structural highs on basement south of the fault are termed the Rockcastle River, Perry County, and Pike County Uplifts (Fig. 4.2). The Perry and Pike County Uplifts are bisected by a north-south embayment or branch of the Rome Trough called the Floyd County Channel (Fig. 4.2). Cambrian strata thicken to thousands of feet within the Rome Trough (Woodward, 1961; McGuire and Howell, 1963; Webb, 1969; Silberman, 1972; Ammerman and Keller, 1979; Sutton, 1981; Gao and others, 2000).

Major Fault Systems

Surface faults in Kentucky have been mapped at the scale of 1:24,000 on the 7.5-minute U.S. Geological Survey geologic quadrangle map series and have been compiled into digital databases, available on the Kentucky Geological Survey Web site (www.uky.edu/kgs). Many of the major surface faults (Fig. 4.3) that cut younger rocks are related to or "rooted" in the previously discussed fault systems that offset Precambrian crystalline rocks (Fig. 4.2). The offset relations indicate fault movement that is the same age or younger than the youngest offset rocks. In other cases, movement along basement faults ceased following the Precambrian or Early Cambrian, and these faults were buried by subsequent sedimentation. This is why some faults shown on the basement fault map (Fig. 4.2) do not appear on the surface fault map (Fig. 4.3). The major fault systems in Kentucky are summarized below.

Relative motion along the faults differs, which causes different types of offsets in rock strata. *Normal faults* are faults in which one side of the fault has dropped down relative to the other. *Reverse faults* have the opposite motion; one side is pushed up relative to the other. Normal and reverse faults tend to be near-vertical, or at least relatively high-angle faults. In contrast, *thrust faults* can be horizontal (low-angle) to high-angle. Strata are pushed upward (or up and over) along thrust faults. *Strike-slip faults* are faults in which there is little or no vertical offset, and relative motion is side-to-side or translational. The relative motion along strike-slip faults may be referred to as right-lateral or left-lateral. In complex fault systems, faults may branch or splinter upward through the underlying strata.

Fluorspar District Faults. The Western Kentucky Fluorspar District is a structurally complex area characterized by closely spaced faults. Most faults in the district are high-angle normal faults, but there are also strike-slip and reverse faults (Heyl and others, 1965;

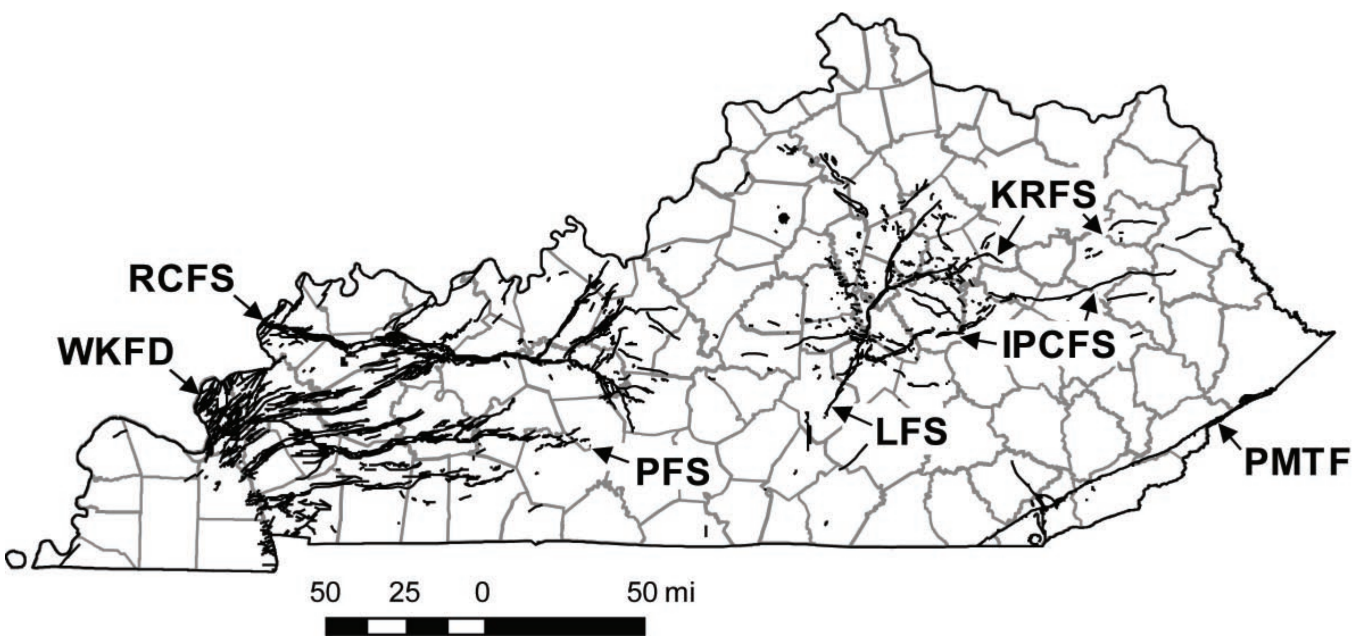

Figure 4.3. Mapped surface faults discussed in this report. IPCF = Irvine–Paint Creek Fault System. KRFS = Kentucky River Fault System. LFS = Lexington Fault System. PFS = Pennyrile Fault System. PMTF = Pine Mountain Thrust Fault. RCFS = Rough Creek Fault System. WKFD = Western Kentucky Fluorspar District faults.

Pinckney, 1976; Trace and Amos, 1984; Nelson and Lumm, 1987; Nelson, 1991; Potter and others, 1995). Faults in this system trend mostly northeast along (and beneath) the eastern margin of the Mississippi Embayment (Figs. 4.1, 4.3). Relative offset of strata suggests that fault movement is mostly post-Pennsylvanian and pre-Mesozoic (Nelson and Lumm, 1987; Potter and others, 1995). Fluorspar mineralization accompanied the migration of fluids along faults associated with Permian igneous intrusions at Hicks Dome, just west of Union County in southern Illinois (Trace and Amos, 1984; Nelson, 1991; Fifarek and others, 2001). Mineralization can fill much of the available pore space in strata near the faults.

Rough Creek Fault System. This system of faults extends east from Union County 130 mi to Edmonson and Hart Counties (Figs. 4.2–4.3). The system consists of a complex series of branching and reconnecting faults. Most of the faults are high-angle normal, although reverse, thrust, and strike-slip faults also occur (Nelson, 1991; Greb and others, 1992). The Rough Creek Fault System marks the northern boundary of the Rough Creek Graben (Fig. 4.2) (Soderberg and Keller, 1981; Nelson, 1991). Normal displacement is mostly down to the south (into the graben), with a maximum offset of 16,000 ft in Webster County, based on seismic analyses. Overall, normal offset diminishes to the east. The Rough Creek Fault System is continuous with the Shawneetown Fault System on the northern boundary of the graben in southern Illinois (Figs. 4.2–4.3). Fault movement was greatest during the Cambrian (see, for example, Potter and others, 1995), but influenced sedimentation through at least the Pennsylvanian Period (see, for example, Greb, 1989).

Pennyrile Fault System. This complex, sinuous zone of faults extends 110 mi from Caldwell County, where faults of the Pennyrile Fault System and Western Kentucky Fluorspar District are difficult to differentiate, east to Edmonson County, where Pennyrile faults can no longer be discerned at the surface (Figs. 4.2–4.3). Faults are mostly high-angle normal, although reverse, thrust, and strike-slip faults have been documented (Schwalb, 1975; Whaley and others, 1979; Lumm and others, 1991a, b; Greb and others, 1992). The Pennyrile Fault System approximately marks the southern boundary of the Rough Creek Graben (Fig. 4.2) (Soderberg and Keller, 1981). A second subparallel series of faults south of the Pennyrile system was considered a southern branch of the system by Lumm and others (1991b), and the actual southern margin of the Rough Creek Graben (Fig. 4.2). The two fault zones create a series of down-to-the-north normal offsets that oppose the down-to-the-south faults of the Rough Creek Fault System. Along the Pennyrile Fault System, the greatest displacement is along the northern faults in the system, with a maximum offset of approximately 4,000 ft. Offset along the faults generally diminishes to the east. Fault movement was greatest in the Cambrian, but influenced sedimentation through at least the Middle Pennsylvanian (see, for example, Lumm and others, 1991; Greb and others, 2001).

Lexington Fault System. This system of generally north–south- and north–northeast- to south–southwest-trending faults can be traced for 80 mi from Casey to Bourbon County (Figs. 4.2–4.3). Faults are mostly high-angle normal, but reverse and strike-slip movements have also been documented (Black and Haney, 1975). Offset along the Lexington faults is mostly down-to-the-east, with maximum displacement of approximately 3,000 ft in Casey and Lincoln Counties, diminishing to less than 1,000 ft to the north and south (Drahovzal and Noger, 1995).

The Lexington Fault System directly overlies the Grenville Front, which is a Precambrian thrust fault marking the western margin of the Grenville Province (see “Precambrian Basement” in the “Rock Unit Summary” section of this chapter). The front extends north in Kentucky to Mason County and south to Wayne County for a total distance of 175 mi. The faults also mark the position of the crest of the Cincinnati Arch along part of their southern extent (Fig. 4.1).

Kentucky River Fault System. This complex, sinuous system of faults extends northeast approximately 110 mi, from its juncture with the Lexington Fault System in Jessamine County, east to Boyd County (Figs. 4.2–4.3). The Kentucky River Fault System has no surface trace across much of its extent but is continuous in the subsurface. Faults are mostly high-angle normal, but reverse, right-lateral, and left-lateral offsets have been documented (Black, 1986; Black and Haney, 1975; Dever, 1999). Faults are rooted in Precambrian basement and form the northern margin of the Rome Trough (Fig. 4.2) (McGuire and Howell, 1963; Ammerman and Keller, 1979). Overall, normal displacement is variable and down-to-the south (into the trough), with 2,700 ft of offset in Jessamine County, 500 ft in Morgan County, and 2,500 ft in Boyd County, based on analysis of seismic and well data (Drahovzal and Noger, 1995). Fault movement was greatest in the Cambrian, but influenced sedimentation through at least the Middle Pennsylvanian (see, for example, Greb and others, 2002; Harris and others, 2004). During the Permian, an igneous kimberlite intruded along the fault in Elliott County (Zartman and others, 1967).

Irvine–Paint Creek Fault System. Faults in this system are approximately 20 mi south of and subparallel to the Kentucky River Fault System (Figs. 4.2–4.3). The Irvine–Paint Creek Fault System extends for 130 mi from its intersection with the Lexington Fault System in Lincoln County, east to Lawrence County. Fault offsets are mostly down-to-the-south, high-angle normal, but reverse, right-lateral, and left-lateral offsets have been documented (Black and Haney, 1975; Black, 1986; Dever, 1999). The Irvine–Paint Creek faults appear to accommodate variable deepening into the Rome Trough (White and Drahovzal, 2002), with down-to-the-south, normal offsets ranging from 5,000 ft in Estill County on the western end of the fault system, to as little as 300 ft in Magoffin and Lawrence Counties on the eastern end of the system (Drahovzal and Noger, 1995). Fault movement was greatest in the Cambrian, but influenced sedimentation through at least the Mississippian and Pennsylvanian (see, for example, Dever, 1999; Greb and others, 2002). The faults continue into West Virginia along a structural upwarping called the Warfield Anticline.

Rockcastle River–Warfield Fault System. The Rockcastle Uplift is an upwarp of strata in Rockcastle County developed above the southern bounding fault of the Rome Trough (Ammerman and Keller, 1979; Drahovzal and Noger, 1995). The bounding fault, called the Rockcastle River Fault, has been projected along the curved western and central parts of the southern edge of the Rome Trough for 105 mi (Fig. 4.2). In western West Virginia, the southern boundary of the Rome Trough is overlain by the Warfield Fault, which can be traced for approximately 15 mi into Kentucky (Fig. 4.2) (Lowry and others, 1990; Gao and Shumaker, 1996). The Rockcastle River and Warfield Faults (and associated basement faults) are separated by 10 to 15 mi. The gap is occupied by the north–south-oriented Floyd County Channel, another Precambrian downwarp, considered part of the Rome Trough (Fig. 4.2).

Pine Mountain Thrust Fault. This large thrust fault defines the northwestern margin of Pine Mountain (Fig. 4.3). At the foot of Pine Mountain (northwest side) the fault dips back into the subsurface at a moderate angle before shallowing to a near-horizontal attitude in the subsurface. The thrust is developed in the Devonian Ohio Shale. The dipping beds at the front of the thrust sheet or hanging wall forms the topographic expression of Pine Mountain. The Pine Mountain Thrust Sheet (the block of earth crust above and southeast of the fault) is 125 mi wide southwest-northeast and 25 mi long southeast-northwest. The thrust block is as much as 2 mi thick and extends under the next overriding thrust sheet to the east.

The northern margin of the Pine Mountain thrust block is the Russell Fork Fault (near Elkhorn City, Ky.) and the southern margin of the thrust block is the Jacksboro Fault (in Tennessee), both of which are strike-slip faults. Lateral offset is greater than 13 mi at the southwestern end of the thrust sheet, but decreases systematically to less than 5 mi at the northeastern end near Elkhorn City, Ky. (Rich, 1934; Harris and Milici, 1977; Dean and Moshier, 1989). The Pine Mountain Thrust is the westernmost thrust fault in the Valley and Ridge Province, which extends eastward into the Appalachians. Thrust development in the Valley and Ridge Province occurred in the Late Pennsylvanian and Permian (Mitra, 1988; Dean and Moshier, 1989). The Pine Mountain Thrust Fault is developed above basement strata and does not offset basement, which is why the fault is shown in the surface fault map (Fig. 4.3), but not the basement fault map (Fig. 4.2).

Rock Unit Summary

The following summary characterizes important geologic characteristics of Devonian and older subsurface rocks in the context of carbon storage (Fig. 4.4). The goal of the summary is to provide basic information concerning pertinent rock units and their likely ability to store carbon dioxide or confine a carbon storage reservoir. This topical data compilation is an important first step in any initial evaluation of a site for carbon storage.

The greatest potential for voluminous carbon storage is in saline reservoirs that are older (and consequently deeper) than the Devonian black shales (e.g., below the New Albany Shale in Figure 4.4). Rock units are grouped into a hierarchy with similar or distinct rock types and bedding, termed groups, formations, and members. Some of the younger rock units discussed below are exposed at the surface in Kentucky (or surrounding states), whereas some older rock units, such

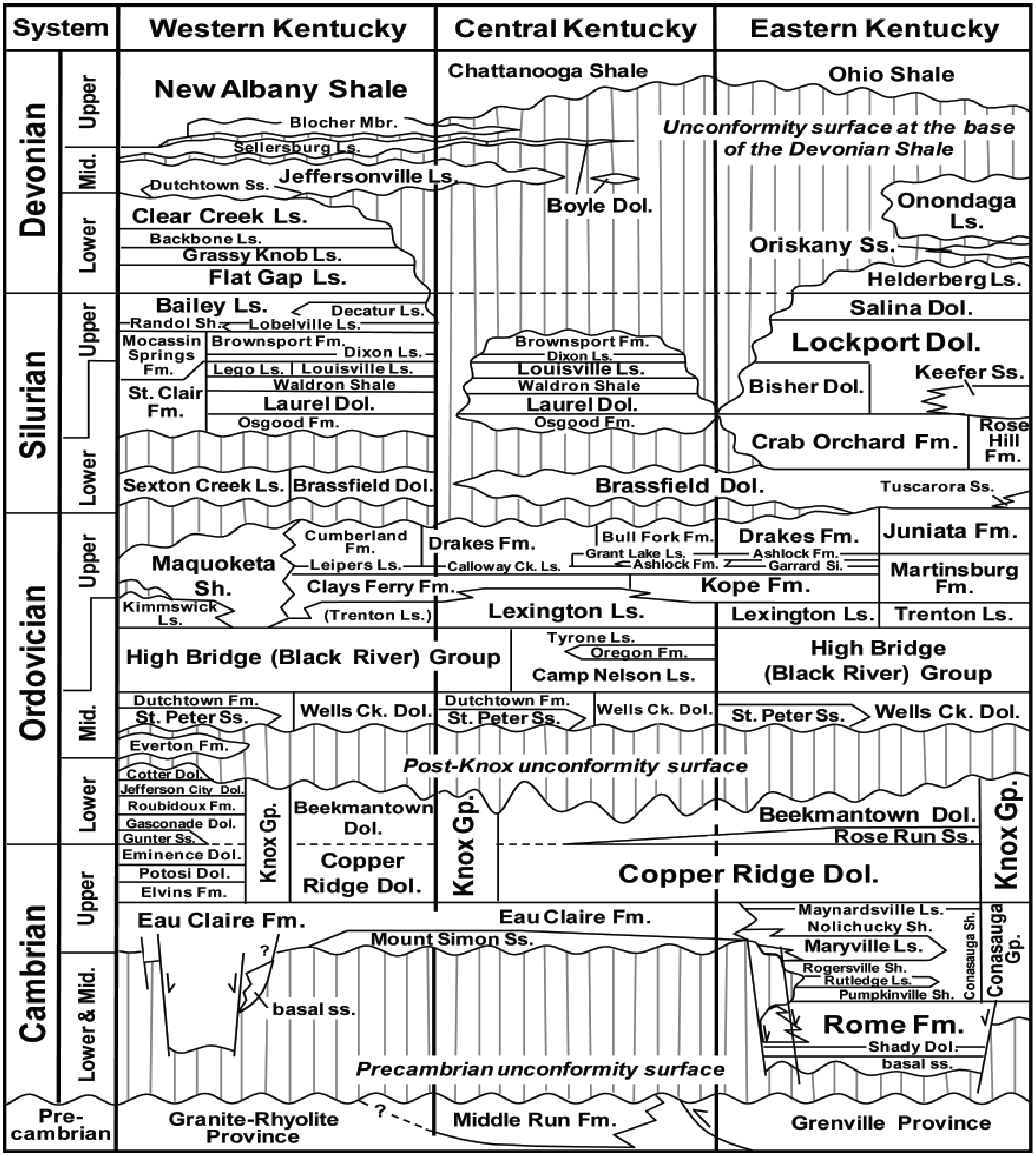

Figure 4.4. Stratigraphic units below the Devonian shales. Vertical lines represent gaps in the stratigraphic record above unconformities. This diagram only represents the nomenclature of units and is not scaled to time or thickness.

as those from the Cambrian System, are only known from subsurface geophysical logging and sampling.

Not all rock units have the same ability to store or confine CO_2, and Figure 4.5 uses color coding to schematically show the variation in storage and confining characteristics. For simplification, multiple rock units with similar carbon storage or confining characteristics are grouped together. Intervals highlighted in Figure 4.5 are discussed in more detail in the following sections.

Potential reservoirs are rock units that contain porosity, which is void space in the rock filled with oil, gas, water, or some combination of these, for some part of their thickness and extent. *Porosity* is the ratio of void volume to total rock volume and is a measure of a reservoir's storage capacity. Another critical reservoir parameter is permeability, which is a measure of the degree to which porosity is interconnected. *Permeability* is the primary control on a reservoir's ability to conduct fluids and therefore is the main influence on the rate at which CO_2 or other fluids can be injected. Neither porosity nor thick, regionally extensive, porous, and permeable sandstones (potential reservoirs colored yellow in Figure 4.5) are considered to be among the most likely candidates for carbon storage. In contrast to the intervals described as potential reservoirs, some geologic units have reservoir-quality rock that has only local potential for storage (reservoirs colored blue-green in Figure 4.5). Collectively, in sequestration parlance, reservoirs capable of storing CO_2 are termed "sinks."

Confining intervals are units consisting primarily of nonporous and mostly impermeable rock. The term "caprock" or "seal" is used in the petroleum industry to denote the confining interval above and sometimes around a reservoir containing oil or natural gas (or both). Similarly, units that form the caprock or seal in CO_2 storage projects will form barriers that will impede migration of CO_2 out of the injection reservoir. The importance of sealing cannot be overstated since it is critical for storage over periods of thousands to tens of thousands of years. Thus, it is critical to identify and characterize caprocks, which in Kentucky consist primarily of shale or carbonate (green- and blue-shaded intervals in Figure 4.5, respectively).

The largest producer of natural gas in Kentucky is the Devonian organic-rich shales (e.g., New Albany Shale) (Figs. 4.4–4.5). These shales are unique in that they are a source of gas — hence a reservoir — but they also act as a seal. The shales consist of fine-grained material that has low permeability and therefore allows the rock to act as a seal. The same fine-grained material also contains abundant organic matter, the surface of which adsorbs methane (as discussed in the introduction), the principal component in natural gas. Once pressure in the shale reservoir drops below a critical threshold, the methane desorbs from the surface of the organic matter and can be produced to a wellbore. Research at KGS by Brandon Nuttall has shown that desorption of methane might be enhanced by injecting CO_2 into the Devonian shales (Nuttall and others, 2005).

Several of the other potential shale confining intervals (light green in Figure 4.5) also have sections with high organic carbon content, but natural gas has not been produced from them in Kentucky, so they are not considered as unconventional reservoirs herein. Adsorptive mechanisms in parts of these shales are possible, as indicated in the rock-unit descriptions of the following section.

There are also rock units that are mostly confining intervals, but locally contain porous intervals that may have carbon storage potential (light blue units in Figure 4.5). In these units, porosity — characterized mostly from oil and gas exploitation — is generally local in extent or confined to discrete zones that represent a small part of the larger nonporous formation, member, or group.

In Figures 4.4 and 4.5, there are gaps in which no rock-unit names are shown (shading with vertical bars). These represent gaps in the geologic record above unconformities (not gaps or caverns in the rock layering), which are surfaces that mark the missing section. Unconformities are extremely important to recognize in subsurface reservoir analysis because the processes of erosion and weathering that formed the surfaces commonly led to alteration (in some cases porosity development) in strata beneath them. Also, unconformities are commonly associated with abrupt changes in rock type, porosity, and permeability. The changes can lead to confining (sealing) properties along the unconformity. Many oil and gas fields are known to occur downdip from unconformity surfaces.

Igneous and metamorphic rocks also occur in the deep subsurface of Kentucky. Basalts are volcanic rocks representing ancient lava flows. The potential for storage of CO_2 in basalts in Kentucky is highly speculative (purple in Figure 4.5). Crystalline metamorphic and igneous rocks (pink in Figure 4.5) do not have storage potential and would be confining intervals (seals),

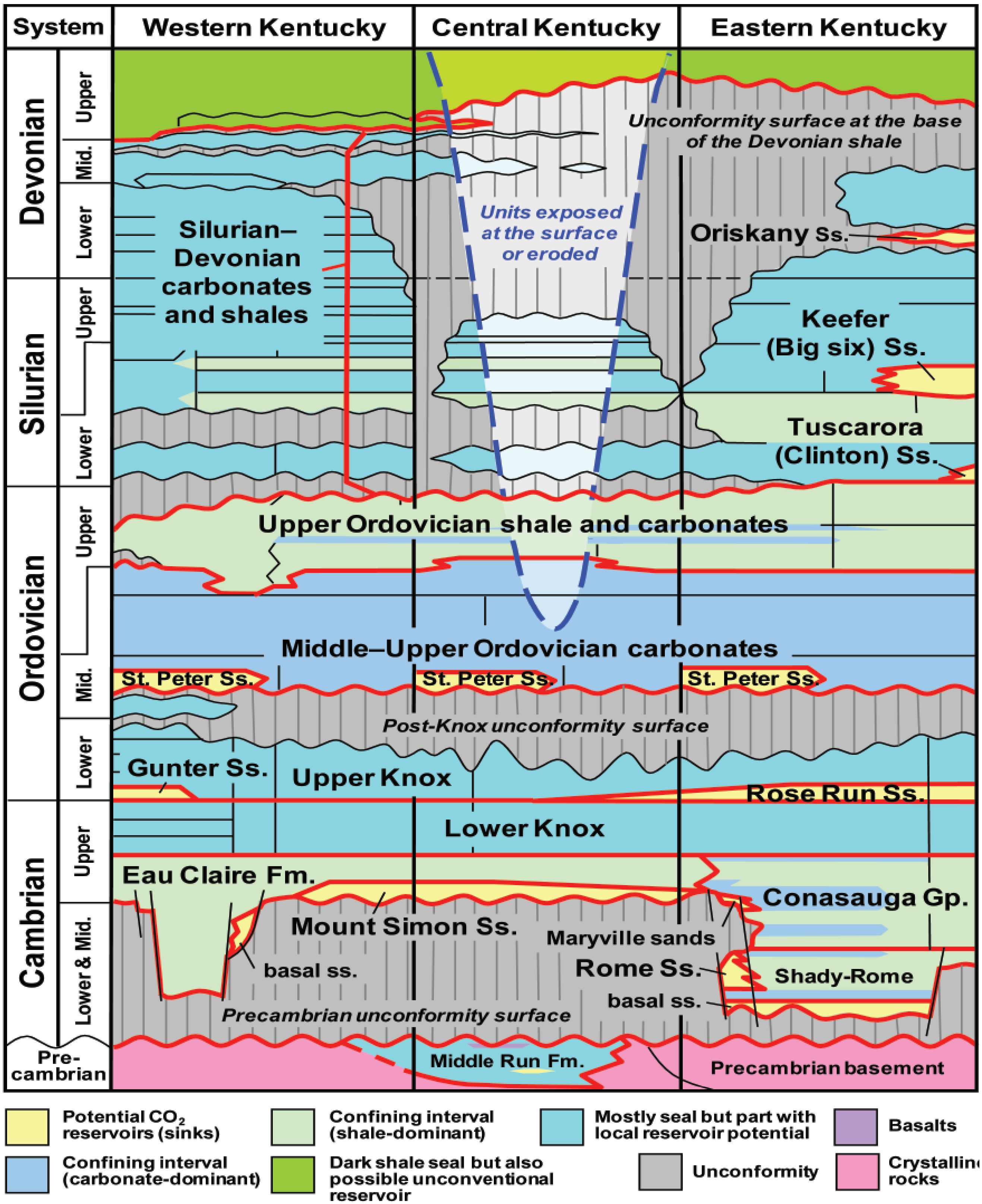

Figure 4.5. Stratigraphic intervals used in this report and their potential as carbon storage reservoirs or confining intervals. The blue dashed line indicates exposure (subcrop) of units into central Kentucky, down to the level of the Ordovician carbonates.

but for the most part do not have underlying reservoir potential beneath them.

The following rock unit descriptions are arranged, in general, from oldest (and deepest) to youngest (and shallowest). Each description begins with a series of outlined parameters to quickly indicate whether the unit is being investigated as a reservoir or seal, the part of the state in which the unit occurs, and the amount of data that the description is based upon.

1. *CO_2 unit type*: Modifier to describe if part of the unit or interval is a potential regional or local reservoir, or confining (sealing) unit.
2. *KGS stratigraphic code*: Modifier used in searches for electronic data in the Kentucky Geological Survey Oil and Gas Database (searchable online at www.uky.edu).
3. *Series/system*: Regional geologic system or series to which the unit or interval belongs (e.g., Cambrian, Ordovician, etc.).
4. *Thickness*: General thickness range for the unit or interval.
5. *Distribution*: Areas of Kentucky in which the unit or interval is found in the subsurface.
6. *Number of wells with completions*: Number of wells for which the unit or interval of interest, defined by the KGS stratigraphic code, was reported as an oil and/or gas producer. This number is an indicator of wells with known porosity (because the unit contained oil or natural gas), and data that might be used to evaluate porosity in a unit or interval of interest. It does not include wells that encountered saline water but not oil or gas.
7. *Number of wells that TD*: Number of wells in which this unit is listed as the bottom of the well (TD = total depth) in the KGS Oil and Gas Database. Fewer wells are available for deeper zones. Also, distribution or spacing of wells is not even for wells that reach TD in any formation. More wells will tend to concentrate where those units occur at relatively shallow depths. The TD number only indicates the number of wells that bottomed in a particular formation. In many cases, that will only be in the upper part of the TD formation, so these wells may not provide information for the entire formation listed as the TD unit. Deeper wells that go through the formation, and include it, are estimated in wells that penetrate any unit.
8. *Approximate number of wells drilled through unit*: This is approximated based on the number of TD's in the underlying unit. This number provides a relative estimate of the amount of data available to examine for subsurface evaluations of thickness, rock type, and porosity of the unit. Fewer wells are available for deeper zones. Also, the distribution or spacing of wells that penetrate any unit is not even.
9. *Interval definition*: Definition of the described unit. Some intervals are the same as a formal stratigraphic rock unit, whereas others are a combination of multiple units with similar properties relative to geologic CO_2 storage.
10. *General description*: Unit or interval characteristics, including rock types, bedding types, and other information pertinent to CO_2 storage. For many units, statewide thickness and structure (elevation at the top of the unit) maps are provided in this report.
11. *Known reservoirs or types of porosity*: Summary of specific oil-, gas-, or saline-water-bearing intervals in the unit, as well as other information that might be pertinent to CO_2 storage in these intervals, such as porosity or permeability measurements.
12. *Overlying sealing/confining units*: The units likely to be secondary, primary, or ultimate seals for the reservoir unit of interest. The primary seal is the immediate seal above the reservoir, which in some cases may be part of the same rock unit as the potential reservoir. Secondary seals are any overlying units with confining properties that will aid in impeding vertical migration of injected fluids. The ultimate seal is an overlying confining interval of regional extent.
13. *CO_2 storage potential*: Qualitative, and in some cases quantitative, summary of the unit's statewide storage potential based on phase I evaluations by U.S. Department of Energy regional carbon sequestration partnerships.

Precambrian Basement

CO_2 unit type: confining unit (but no underlying reservoirs)
KGS stratigraphic code: 400BSMN, 400GRRY, 400GRVB

Series/system: Precambrian
Thickness: does not apply
Distribution: statewide
Number of wells with completion: 0
Number of wells that TD: 51
Approximate number of wells drilled through unit: 0

Interval Definition. Basement includes Precambrian metamorphic and igneous rocks (sometimes referred to as "crystalline") beneath the Precambrian unconformity. These rocks are often referred to as the basement upon which younger, mostly sedimentary rocks were deposited (Figs. 4.4–4.5). There are three types of Precambrian rock in Kentucky, of which two consist of crystalline rocks and represent the basement; the third, called the Middle Run Formation, is a thick succession of sedimentary and igneous rocks above basement (Fig. 4.6).

General Description. In western Kentucky, the Precambrian basement consists of igneous rocks (rhyolites, trachytes, and fine-grained granites), termed the Granite-Rhyolite Province (Denison and others, 1984; Bickford and others, 1986; Drahovzal and others, 1992). In eastern Kentucky the basement consists of metamorphic rocks that are part of the Grenville Province (Keller and others, 1983; Black, 1985; Drahovzal and others, 1992). The boundary between the two provinces is a thrust fault, called the Grenville Front, which extends from Canada south into Alabama (Keller and others, 1982; Denison and others, 1984; Green and others, 1988; Hoffman, 1989). In Kentucky, the Grenville Front extends from Mason to Bracken Counties and in part coincides with the trace of the Lexington Fault System (Figs. 4.3, 4.6).

Using sea level as a reference datum, in which depths are given as values below sea level, the top of the Precambrian (Precambrian unconformity surface) varies from –2,000 ft near the Grenville Front in central Kentucky to more than –30,000 ft in western Kentucky (Fig. 4.6). Sharp changes in depth and steep dips (relatively closely spaced contour lines) on the Precambrian structure map (Fig. 4.7) in eastern and western Kentucky correspond to the increased depth to basement in the Rome Trough and Rough Creek Graben, respectively (Fig. 4.2). The deepest part of the Rough Creek Graben in western Kentucky is more than –30,000 ft in Webster County, just south of the Rough Creek Fault System. In contrast, the deepest part of the Rome Trough in eastern Kentucky is –17,000 ft in northern Pike and southern Martin Counties. West of the Grenville Front in central Kentucky (Fig. 4.7), the top of the Precambrian coincides with strata of the Middle Run Formation rather than crystalline basement, which is below the Middle Run and locally may be more than 20,000 ft deeper than the top of the Precambrian (Drahovzal and others, 1992).

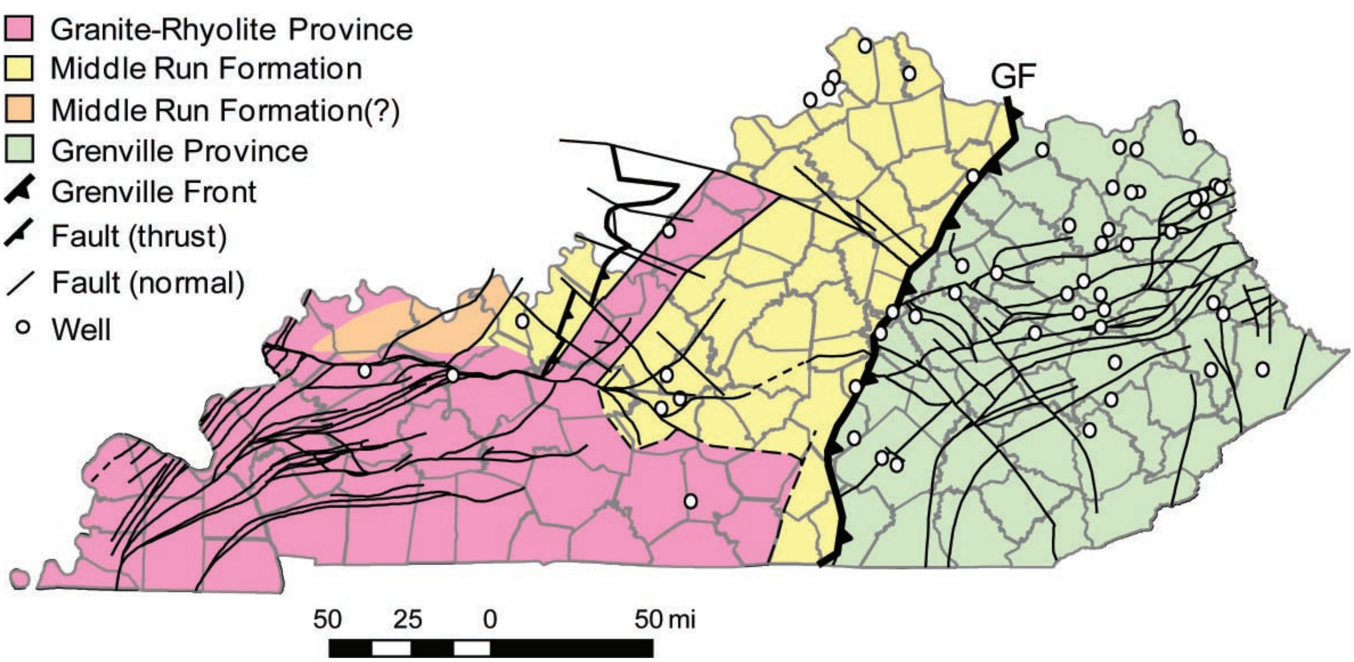

Figure 4.6. Precambrian rocks. Modified from Drahovzal (2002). The Granite-Rhyolite Province underlies the Middle Run Formation. GF = Grenville Front.

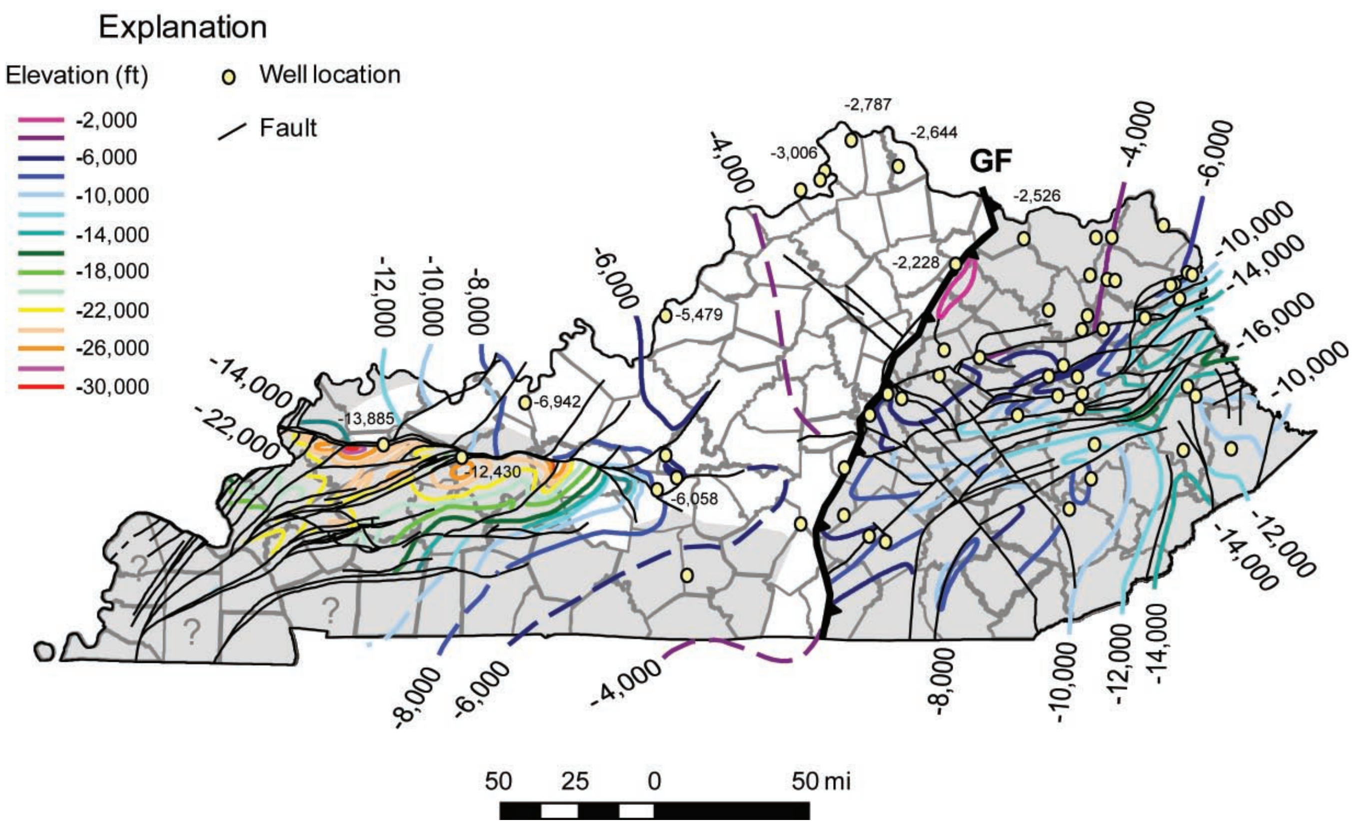

Figure 4.7. Structural elevation on top of the Precambrian unconformity. Precambrian crystalline basement beneath the unconformity is shown in gray. Areas of potential Middle Run Formation beneath the unconformity are shown in white. Contour values refer to depths below sea level. Eastern Kentucky data from Drahovzal and Noger (1995). Western Kentucky data from preliminary assessment of seismic data by Jim Drahovzal (Kentucky Geological Survey). Where the Middle Run Formation is preserved (white), Precambrian crystalline basement would be deeper than shown. Datum is sea level. GF = Grenville Front.

Fifty-five wells have been drilled into the Precambrian in Kentucky; eight are in the sedimentary Middle Run Formation, rather than crystalline basement. Most Precambrian basement wells are in eastern Kentucky; only four are in western Kentucky. Because of the relatively few Precambrian wells in the state, the structure map (Fig. 4.7) is largely constructed from seismic, magnetic, and gravity data.

Precambrian basement strata are significant to carbon storage for two reasons. First, by far the majority of sedimentary rocks having porosity and permeability to act as reservoirs occur above the Precambrian basement. Therefore, the Precambrian basement represents a depth limit to potential carbon storage. Second, many of Kentucky's major fault systems are rooted in Precambrian basement and cut up through younger and shallower sedimentary rocks that might be suitable for carbon storage (see, for example, Drahovzal and Noger, 1995; Harris and others, 2004). Accurately documenting the offsets by faults, the amount of relative movement along faults, and whether the faults are potentially leaking or sealing will be important for any CO_2 storage project.

Known Reservoirs or Types of Porosity. Precambrian metamorphic and igneous rocks in the Granite-Rhyolite and Grenville Provinces generally have no porosity.

Overlying Sealing/Confining Units. Precambrian metamorphic and igneous rocks in the Granite-Rhyolite and Grenville Provinces would be confining units if any porous or permeable zones occurred within or beneath them.

CO_2 Storage Potential. Precambrian metamorphic and igneous rocks in the Granite-Rhyolite and Grenville Provinces have little or no CO_2 storage potential.

Middle Run Formation

CO_2 unit type: potential local reservoirs (unknown to poor potential)
KGS stratigraphic code: 400MDLR

Series/system: Precambrian
Thickness: 0–22,500 ft
Distribution: central and parts of western Kentucky
Number of wells with completion: 0
Number of wells that TD: 8
Approximate number of wells drilled through unit: 0

Interval Definition. The Middle Run Formation is a Precambrian succession of sedimentary and volcanic rocks capped by the Precambrian unconformity. The interval described in this report is the same as the formal definition (Shrake and others, 1991; Drahovzal and others, 1992), which is shown in yellow in Figure 4.6, although recent seismic analysis suggests that the unit may extend farther west (shown in orange in Figure 4.6) than previously thought (Drahovzal, 2002).

General Description. The Middle Run Formation consists of red to gray, fine- to medium-grained, feldspathic to quartzose sandstones, siltstones, and shales, and local felsic (composed of light minerals) and mafic (composed of dark minerals) volcanics that fill an irregularly shaped, buried rift basin west of the Grenville Front (Fig. 4.6). Thirty-five wells have penetrated the Middle Run in the Indiana-Ohio-Kentucky region, and nine are in Kentucky (Table 4.1). Thickness and relationships to Precambrian metamorphic and igneous provinces are largely based on seismic, gravity, and magnetic data (Drahovzal and others, 1992; Drahovzal, 1997).

Known Reservoirs or Types of Porosity. Analysis of core, drill cuttings, and wireline logs in the Middle Run indicates low porosity and permeability and therefore an absence of reservoir-quality rock (Drahovzal and others, 1992). One possible exception is the K II No. 1 Brooks well in Hart County (Drahovzal and Harris, 2004; Harris, 2004). The Brooks well penetrated 1,789 ft of Middle Run strata and encountered a possible porous sandstone—informally called the Four sand—at 1,652 ft from the top of the formation (Fig. 4.8). The sandstone is gray to pink, medium-grained, and quartz-rich (quartzarenite to sublitharenite). Based on seismic data, this sand may be as much as 650 ft thick near the well and may thicken to as much as 1,200 ft. It appears to cover an area of approximately 80 mi^2 at depths of 7,000 to 9,500 ft beneath the surface. Cuttings of the basal 157 ft of the sandstone were more quartz-rich (classified as quartzarenites) than were overlying sandstones (classified as sublitharenites), and contained disaggregated quartz grains, which might suggest sparse cement and possible porosity. The suggestion of porosity was confirmed by markedly higher sonic porosity values in the quartz-rich sandstone than in overlying sublitharenites (Drahovzal and Harris, 2004; Harris, 2004). Nine months after drilling, the company tested the Four sand, but the interval did not show any flow response. Unfortunately, quantitative measurements are not available from the testing.

Table 4.1. Wells that drilled into the Precambrian Middle Run Formation in Kentucky. Updated from Drahovzal and others (1992). Information about these wells is available online at the Kentucky Geological Survey Web site. Two wells do not have permit numbers. To aid in online searches for those wells, the KGS record number for the California Spears well is 12452 and for the Ford Conner well is 2343.

Well Name	*Permit No.*	*County*	*Precambrian Top (ft subsea)*	*Middle Run Thickness Penetrated (ft)*	*Rock Types*
Ashland Oil No. 1 Wilson	18051	Campbell	–2,745	58	arkosic sandstone and siltstone, basalt
Battelle No. 1 Duke Energy	138119	Boone	–3,006	168	arkosic sandstone and siltstone
California No. 1 Spears	none	Lincoln	–4,609	357	rhyolite
Ford No. 1 Conner	none	Boone	–2,807	371	arkosic sandstone and siltstone
Ky. Geol. Survey No. 1 Blan	137114	Hancock	–7,491	542	arkosic sandstone and siltstone
Ky. Oper. No. 1 Sherrard	88556	Larue	–6,074	298	arkosic sandstone and siltstone
Ky. Oper. No. 1 Riordan	87916	Hart	–6,846	489	arkosic sandstone and siltstone
K II No. 1 Brooks	89059	Hart	–5,754	1,789	arkosic sandstone and siltstone, quartzose sandstone
Texaco No. 1 Sherrer	18114	Jessamine	–2,326	2,008	arkosic sandstone and siltstone, quartzose sandstone, basalt

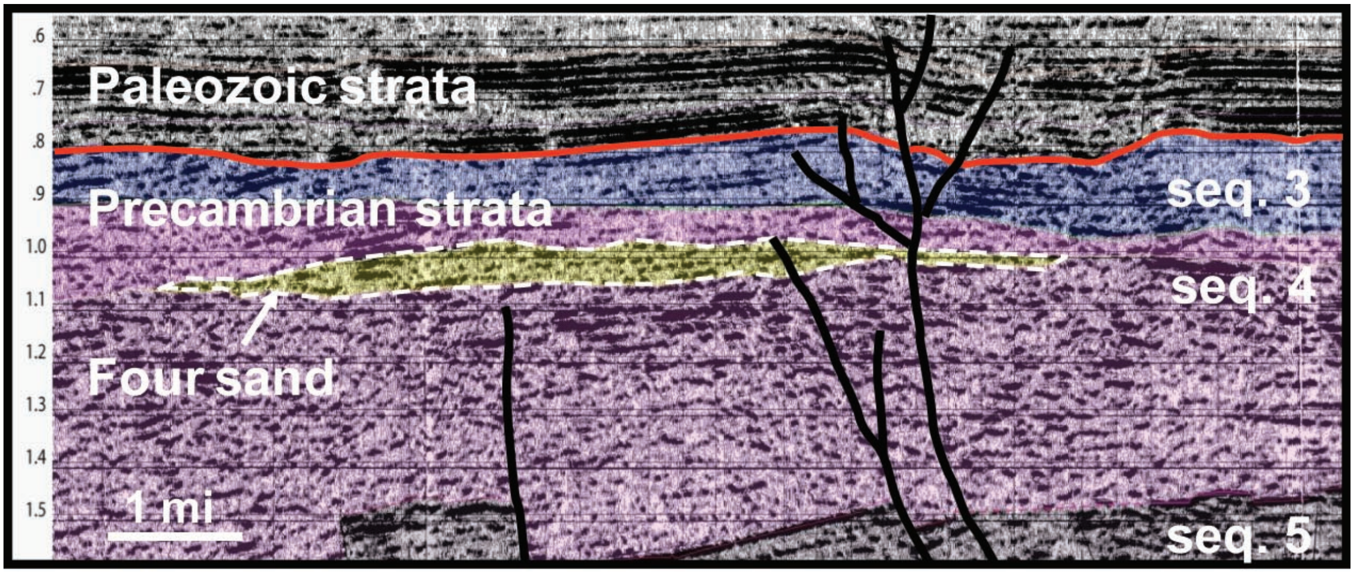

Figure 4.8. Seismic record from Hart County, near the K II No. 1 Brooks well, showing interval interpreted as the Four sand (interpretation from Jim Drahovzal, Kentucky Geological Survey). The Precambrian is broadly divided into sequences (labled as seq. 3, seq. 4, seq. 5) based on seismic attributes. Hence, the Four sand falls into the broader sequence 4.

Overlying Sealing/Confining Units. If the Four sand or similar Middle Run sandstone bodies were used for carbon storage, the overlying and adjacent thick sequences (seq. 3 and 4 in Figure 4.8) of likely non-porous quartz-poor sandstones, siltstones, and shales would form the immediate confining unit. The Precambrian unconformity surface could be a secondary seal. Thick shales of the Cambrian Eau Claire Formation would likely be the ultimate seal (Fig. 4.5).

CO_2 Storage Potential. Because so few data are available, little can be said about the Middle Run's carbon storage potential; therefore, it would be risky to assume that it has storage potential at this time. None of the wells that have sampled the upper parts of the Middle Run Formation have encountered porous or permeable sandstones. The identification of the deeper Four sand from seismic analysis, however, suggests that there is at least the possibility of local, deeper reservoirs in the Precambrian on the Cincinnati Arch.

Another possibility for future carbon storage in the Middle Run is basalts. Two wells have encountered basalts, the Texaco No. 1 Sherrer well in Jessamine County and the Ashland No. 1 Wilson well in Campbell County (Table 4.1). The Ashland No. 1 Wilson well encountered two thick basalt flows. As with the Middle Run sandstones, however, little is known about the extent, thickness, and magnitude of porosity in the basalts, so their storage potential is speculative, and they are not considered further herein.

Basal Sandstone (Eastern Kentucky)

CO_2 unit type: potential regional reservoir (unknown to poor potential)
KGS stratigraphic code: 375BASAL, 375ARKS
Series/system: Cambrian
Thickness: 0–313 ft.
Distribution: southeastern Kentucky (Rome Trough)
Number of wells with completion: 0
Number of wells that TD: 10
Approximate number of wells drilled through unit: 31

Interval Definition. The term "basal sandstone" refers to sandstones of different ages and composition that were deposited on top of the Precambrian unconformity (Figs. 4.4–4.5, 4.9). Sandstone deposited on top of the Precambrian unconformity north of the Rome Trough and Rough Creek Graben is formally called the Mount Simon Sandstone, whereas south of the Rough Creek and Kentucky River Fault Systems in the Rome Trough of southeastern Kentucky the sandstone is informally called the basal sandstone. This basal sandstone, located between the Precambrian unconformity and the Shady (Tomstown) Dolomite, is older and different than the Mount Simon Sandstone. There is also a basal sandstone in the Rough Creek Graben, which is discussed separately herein. Unless a connection can

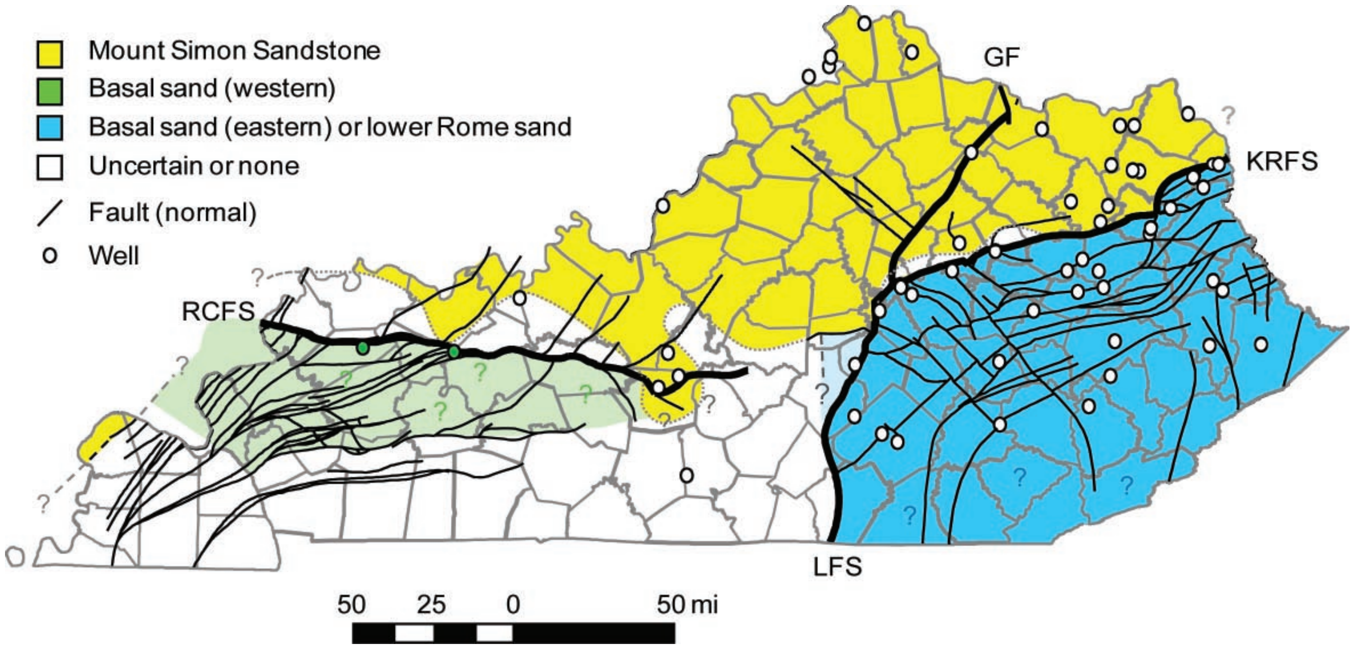

Figure 4.9. Distribution of sandstones above the Precambrian unconformity surface. In the Rough Creek Graben of western Kentucky (green shading) a possible basal sandstone has only been documented in two wells on fault blocks (green circles). GF = Grenville Front. LFS = Lexington Fault System. KRFS = Kentucky River Fault System. RCFS = Rough Creek Fault System.

be shown to the formal Mount Simon Sandstone, it is best to consider sandstones above the Precambrian unconformity surface as basal sandstones.

One possible exception to the aforementioned distribution of the basal sand in eastern Kentucky is in Lincoln County, where the California Co. No. 1 Spears well contains a thick sandstone above the Precambrian unconformity. This sandstone is thicker than the Mount Simon to the north and lies beneath a much thicker section of Conasauga Shale (Eau Claire Formation) than in other wells outside of the Rome Trough. These differences and the lack of an obvious connection to the Mount Simon to the north suggest that this sandstone should be included in the basal sandstone interval of eastern Kentucky. Harris and others (2004) inferred that the area of the Spears well might be a western projection of the Rome Trough (dashed north-south line and "?" in Figure 4.9).

General Description. In most areas where the basal sandstone is penetrated in eastern Kentucky (more than 30 wells), the basal sandstone consists of a series of quartz-rich (quartzose) to feldspar-rich (arkosic) sandstones interbedded with siltstones, shales, carbonates, and sometimes evaporites. Sample descriptions from the United Fuels Gas No. 84371 Fordson well in Leslie County indicate a variety of rock types, including a rock described as quartzite (presumably a hard, tight, quartz-rich sandstone, rather than the metamorphic rock quartzite) that is arkosic and partly dolomitic, red and green shales with some pyrite, limestone, and hematite. Analysis of core samples from the Exxon No. 1 Banks well in Wolfe County shows that the basal sandstone at that location contains red and green shales and siltstones, along with nodular evaporites (Harris and others, 2004).

The basal sandstone has variable thickness in the Rome Trough, where it ranges from 0 to 313 ft thick (Fig. 4.10). It is thickest in the Texaco No. 1 Perkins well in Madison County, which is near the intersection of the Lexington and Kentucky River Fault Systems on the northwestern edge of the Rome Trough. Lateral thickness variation may be more complex in eastern Kentucky than indicated in the isopach (thickness) map (Fig. 4.10). The basal sandstone is deepest in the center of the Rome Trough (–16,000 ft below sea level) and becomes shallower west and north toward the margins of the trough (Fig. 4.11).

Known Reservoirs or Types of Porosity. There is no known oil and gas production from the basal sandstone in eastern Kentucky, nor has it been found to have sufficient porosity to serve as a potential carbon storage reservoir. For example, core samples from a 90-ft-thick

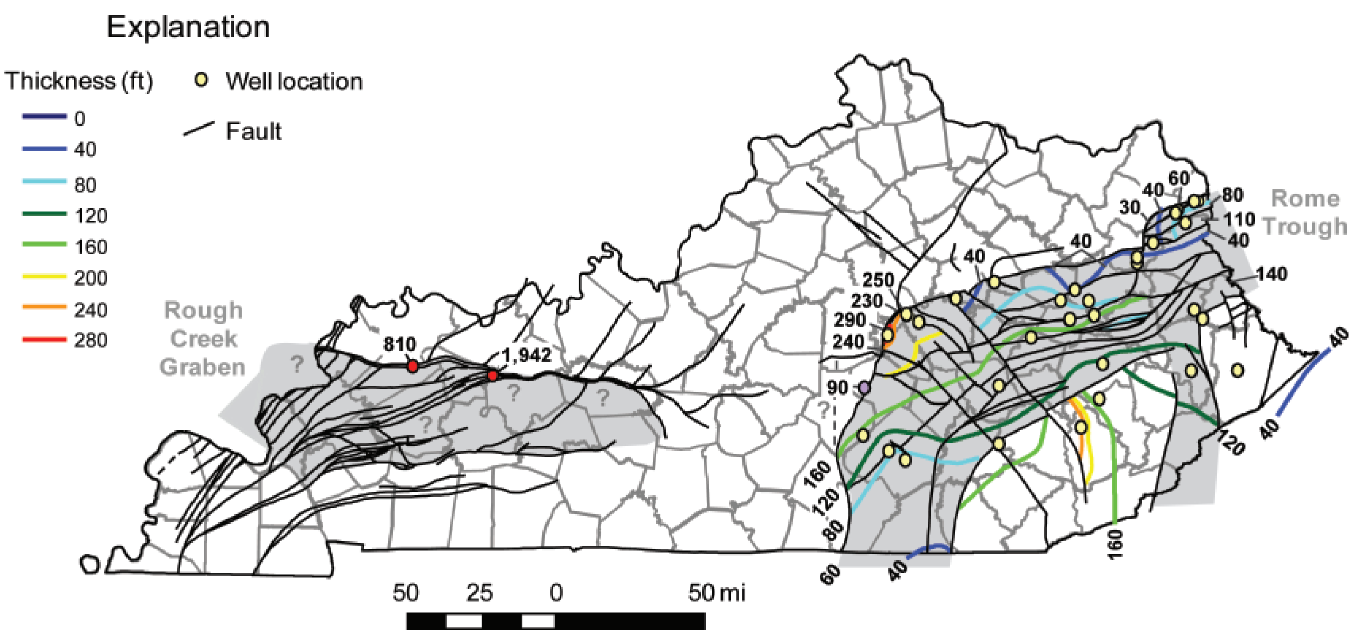

Figure 4.10. Thickness of the basal sandstone interval (may include units that are not sandstone). The basal sandstone is widespread in eastern Kentucky. One well in Lincoln County (purple circle) has a basal sandstone that may represent a westward extension of the Rome Trough. In western Kentucky, two wells (red circles) have thick basal sandstones that are unlikely to be correlative to the Mount Simon Sandstone north of the Rough Creek Graben. The thickness shown here is the thickness of the entire interval and does not indicate porosity or potential reservoir thickness. Only a small part of this thickness and extent (if any) might be available for carbon storage.

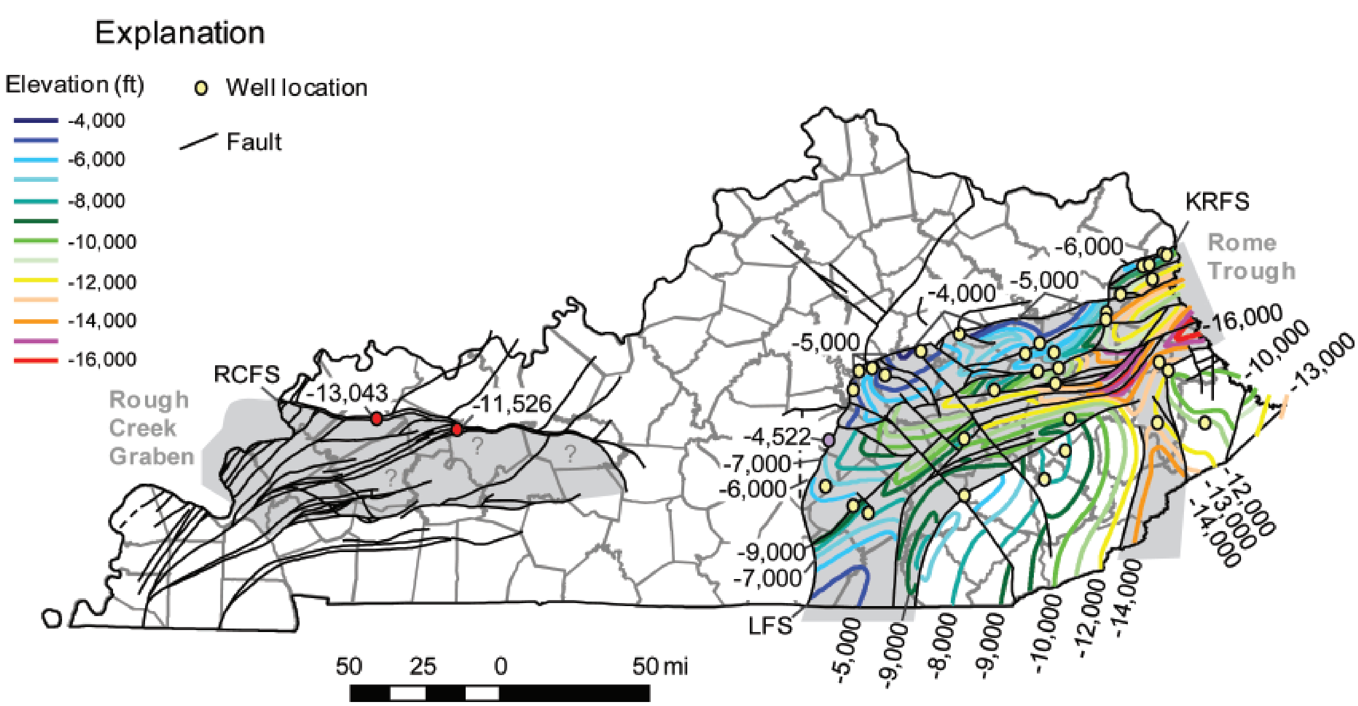

Figure 4.11. Structural elevation of the basal sandstone. In western Kentucky, only two wells penetrate the basal sandstone (red circles), so structural contours are not drawn. There is also a single well in central Kentucky (purple circle) that may contain an eastern basal sandstone outside of the Rome Trough. Datum is sea level.

sandstone at a depth of 5,110 to 5,720 ft in the California No. 1 Spears well in Lincoln County had 0.6 to 2.8 percent porosity and little permeability.

Overlying Sealing/Confining Units. If porosity is found in the basal sand and it is suitable for CO_2 storage, the overlying Shady (Tomstown) Dolomite would form the main confining unit (Figs. 4.5, 4.12). Where the Shady is absent, say from faulting, thick shales of the lower Rome Formation would be the principal confining unit. Stratigraphically higher secondary seals would include the Conasauga shales and carbonates, thick and dense Knox carbonates, High Bridge–Trenton carbonates, Upper Ordovician Clays Ferry shales, and ultimately, in some areas, the Devonian Ohio Shale (Fig. 4.5).

CO_2 Storage Potential. Insufficient core and well-log data are available to make a quantitative assessment of the basal sand's storage potential, although current data suggest little potential for large-scale CO_2 storage. More study of framework grain composition and the potential for secondary porosity development is needed.

Shady-Rome (Nonsandstone) Interval

CO_2 unit type: confining unit
KGS stratigraphic code: 375SHDY, 375TMSN, 375ROME
Series/system: Cambrian
Thickness: 0–228 ft (Shady), 0–2,613 ft (Rome)
Distribution: southeastern Kentucky (Rome Trough)
Number of wells with completion: 0
Number of wells that TD: 2
Approximate number of wells drilled through unit: 37

Interval Definition. In southeastern Kentucky, the basal sandstones are overlain by a thick sequence of clastics and carbonates termed the Shady (Tomstown) Dolomite (Figs. 4.4–4.5, 4.13). The Shady, as defined by Harris and others (2004) and previous subsurface researchers (e.g., McGuire and

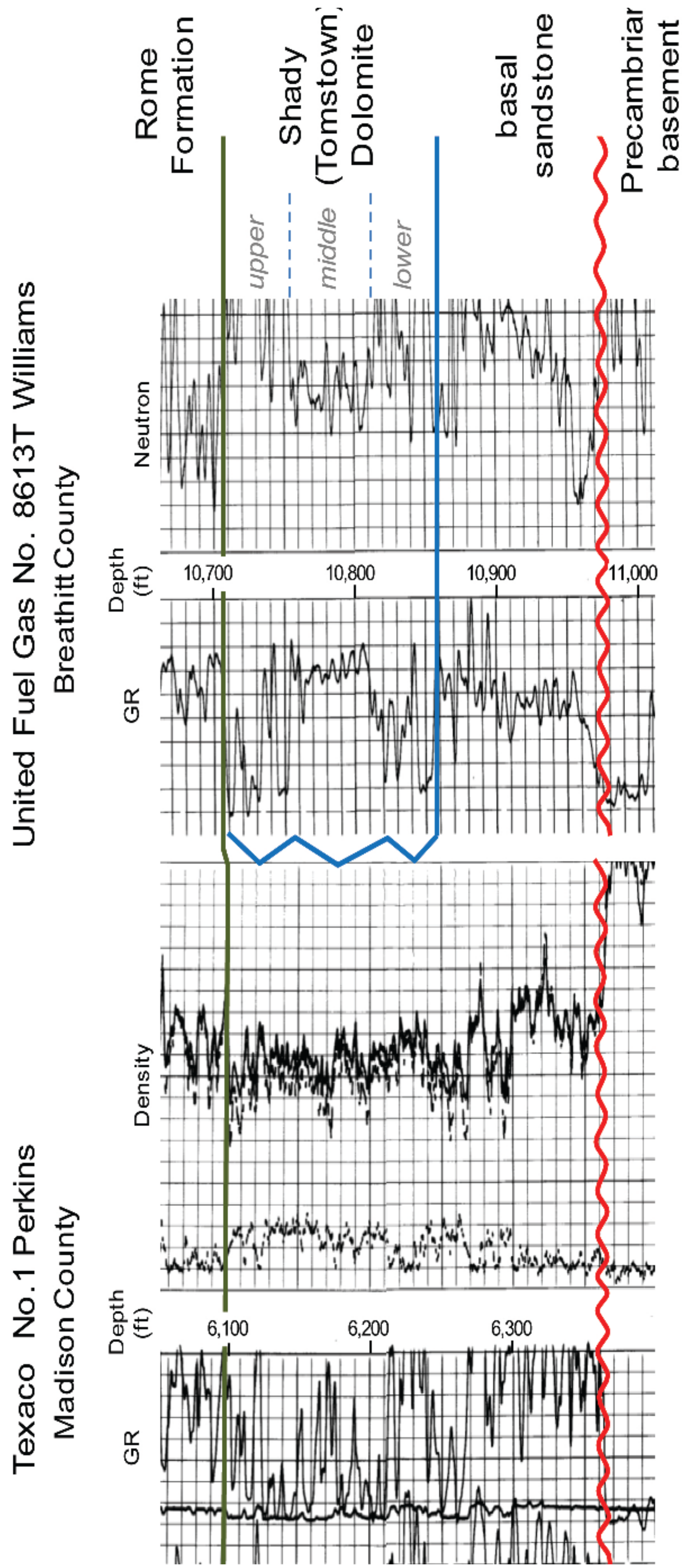

Figure 4.12. Geophysical logs of the basal sandstone and overlying confining units in southeastern Kentucky. GR=gamma ray.

Howell, 1963), extends from the top of the uppermost sandstone of the basal sandstone to the top of the uppermost dolomite in the overlying mixed shale and carbonate succession. The Shady (Tomstown) Dolomite is overlain by the Rome Formation, the lower part of which is shale-dominated. Along the northern margin of the Rome Trough, however, the middle and upper Rome contains significant sandstone bodies (Fig. 4.13), which are discussed in the next section. In this section, the Shady (Tomstown) Dolomite and shale-dominant parts of the Rome are discussed as a single confining interval for the basal sandstone (Fig. 4.12).

General Description. Neither the Shady Dolomite nor Rome Formation crop out at the surface in Kentucky, so descriptions are based solely on well samples. The Shady Dolomite is a white, gray, and brown, finely crystalline, sandy to argillaceous dolomite, limestone, and shale (McGuire and Howell, 1963). Sample descriptions from the United Fuels Gas No. 84371 Fordson well in Leslie County, record an organic-rich shale (similar to the dark shales found in the lower Rome Formation) interbedded with the dolomite.

The Shady (Tomstown) Dolomite ranges from 0 to 228 ft thick in southeastern Kentucky. It thickens to the south, and is as much as 1,200 ft thick in Tennessee and Virginia (Harris and others, 2004). The upper contact of the Shady may be unconformable with the Rome Formation (Read, 1989; Ryder, 1992).

The overlying Rome Formation consists of shales, siltstones, sandstones, and carbonates, which fill the Rome Trough and extend southward into Tennessee and Virginia (Ryder, 1992; Ryder and others, 1996, 1997; Harris and others, 2004). The Rome reaches a maximum drilled thickness of 2,613 ft in the United Fuel Gas No. 8801A Knuckles well in Bell County. Shales are green, red, purple, gray, glauconitic, and sometimes silty (McGuire and Howell, 1963). In the United Fuels Gas No. 84371 Fordson well in Leslie County, the basal 20 ft of the Rome is a carbonaceous, dark brown to black shale. South of Kentucky, red beds are reported from the Rome Formation (Read, 1989a), but in Kentucky and West Virginia the rocks are predominantly green-gray, marine facies (McGuire and Howell, 1963; Harris and others, 2004). Siltstones are glauconitic and micaceous.

The top of the Rome is marked by a thick brown to gray, very finely crystalline, and partly oolitic limestone across much of eastern Kentucky (McGuire and Howell, 1963; Ryder and

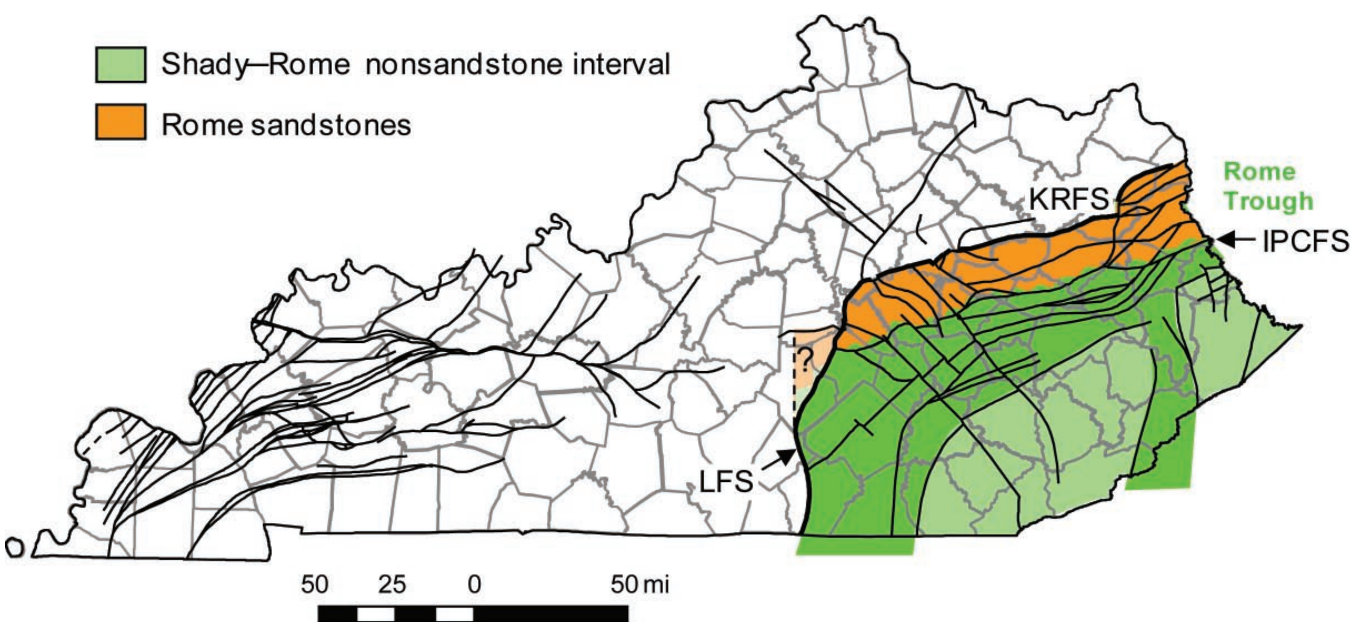

Figure 4.13. Distribution of the Shady-Rome confining interval (green), which includes the Rome Formation where it does not contain thick, porous sandstones, and the area in which the Rome Formation contains thick sandstones (orange). The boundary is transitional, but close to the Irvine–Paint Creek Fault System (IPCFS). Some Rome sandstones may extend into western Lincoln and eastern Casey Counties (area shown with a ?). KRFS = Kentucky River Fault System. LFS = Lexington Fault System. Rome Trough (darker green) includes Rome sandstones (orange).

others, 1992a; Harris and others, 2004). The limestone is present in the deeper parts of the Rome Trough, but is absent north of the Irvine–Paint Creek Fault System.

Known Reservoirs or Types of Porosity. No oil or gas is produced from the Shady and lower Rome (where thick sandstones are absent), and the lack of porosity in these rocks suggests that they are more likely to serve as confining intervals. Also, the thick limestone at the top of the Rome exhibits low porosity on downhole density logs and would likely act as a seal.

CO_2 Storage Potential. The Shady and Rome (where thick sandstones are absent) interval is a seal or confining interval. It has little or no carbon storage potential.

Rome Sandstones

CO_2 unit type: potential regional or local reservoir (good potential)
KGS stratigraphic code: 375ROME
Series/system: Cambrian
Thickness: 0–1,186 ft
Distribution: southeastern Kentucky (Rome Trough)
Number of wells with completion: 25
Number of wells that TD: 54
Approximate number of wells drilled through unit: 87

Interval Definition. The Rome sandstones are part of the Rome Formation. The interval is defined as the sandstone-dominated part of the Rome Formation (Figs. 4.4–4.5). These sandstones are concentrated along the northern margin of the Rome Trough in eastern Kentucky between the Kentucky River Fault System and the Irvine–Paint Creek Fault System. The nonsandstone-dominated parts of the Rome were treated separately in the preceding section as part of the Shady-Rome confining interval.

General Description. Rome sandstones consist of coarse to very fine-grained, quartzose to arkosic, micaceous, and glauconitic sandstone with angular to subrounded grains (McGuire and Howell, 1963; Sutton, 1981; Harris and Baranoski, 1996; Harris and others, 2004). Along the northern margin of the Rome Trough, the thickest sandstones are concentrated in (1) a small area extending through parts of Jessamine, Garrard, and Madison Counties (Figs. 4.14–4.16) and (2) a broader area in parts of Menifee, Morgan, Elliott, and Boyd Counties (Figs. 4.15, 4.17). The maximum thickness of the Rome sandstone interval is 1,186 ft in the Ashland Kazee No. 1 well of Elliott County. The interval also contains shales and sandy shales (Figs. 4.18–4.19). The number of sandstones and total sandstone thickness is greatest immediately adjacent to the Kentucky River Fault System, and decreases south toward the Irvine–Paint Creek Fault System (Fig. 4.15; Harris and others, 2004). Few wells penetrate the sandstones, but heterogeneity is likely based on the rapid, southward transition into a shale-dominated Rome Formation.

Known Reservoirs or Types of Porosity. Twenty-five wells recorded completions in the Rome sandstones. Some wells report multiple completion intervals. Fourteen of the wells with reported completions are in the Homer Field (previously Isonville and Isonville Consolidated Fields) of Elliott County (Fig. 4.18). Data from the Homer and other Rome fields in Kentucky and West Virginia have been summarized by Harris and Baranoski (1996), and Harris and others (2004).

An example of the type of reservoir that might be encountered in Rome sandstones on the northern margin of the Rome Trough is the Homer Field in Elliott County, the largest producer of hydrocarbons from the Rome sandstone in Kentucky. The Carson Associates No. 57 Prichard Heirs well was the first well to begin production from the pre-Knox section in January 1997. Production from the Rome came from three informally named sandstones: the Prichard sand, Lawson sands, and Oliver sand (Figs. 4.18–4.19). The Prichard consists of 15 to 20 ft of shaly sandstone, situated 125 to 150 ft beneath the top of the Rome (60 to 80 ft below the top of the lower unit of the Rome defined by Harris and others [2004]). Porosities calculated from density and neutron logs range from near 0 to 5 percent. The Lawson sands are 275 to 300 ft below the Prichard sand (Fig. 4.18), and consist of a series of alternating clean and shaly sandstones. The Lawson sandstones are 65 to 85 ft thick and have porosities calculated from downhole logs of 0 to 10 percent. The Oliver sandstone is 300 to 325 ft below the base of the Lawson sands, and consists of 10 to 15 ft of sandstone (Fig. 4.19). Porosities calculated from geophysical logs range from 0 to 8 percent.

Rodvelt and others (1999) summarized the case history of a well in Lawrence County that used CO_2 foam for stimulation in a Rome sandstone reservoir. Nineteen sidewall cores taken from Rome sandstones had an average porosity of 9 percent, and a range of porosities and permeabilities of 5.0 to 9.9 percent, and 0.17 to 2.23 md, respectively. In the well, 17,631 gallons of CO_2 foam were used with 14,014 lb of 20/40 mesh Ottawa sand at depths of 7,156 to 7,176 ft

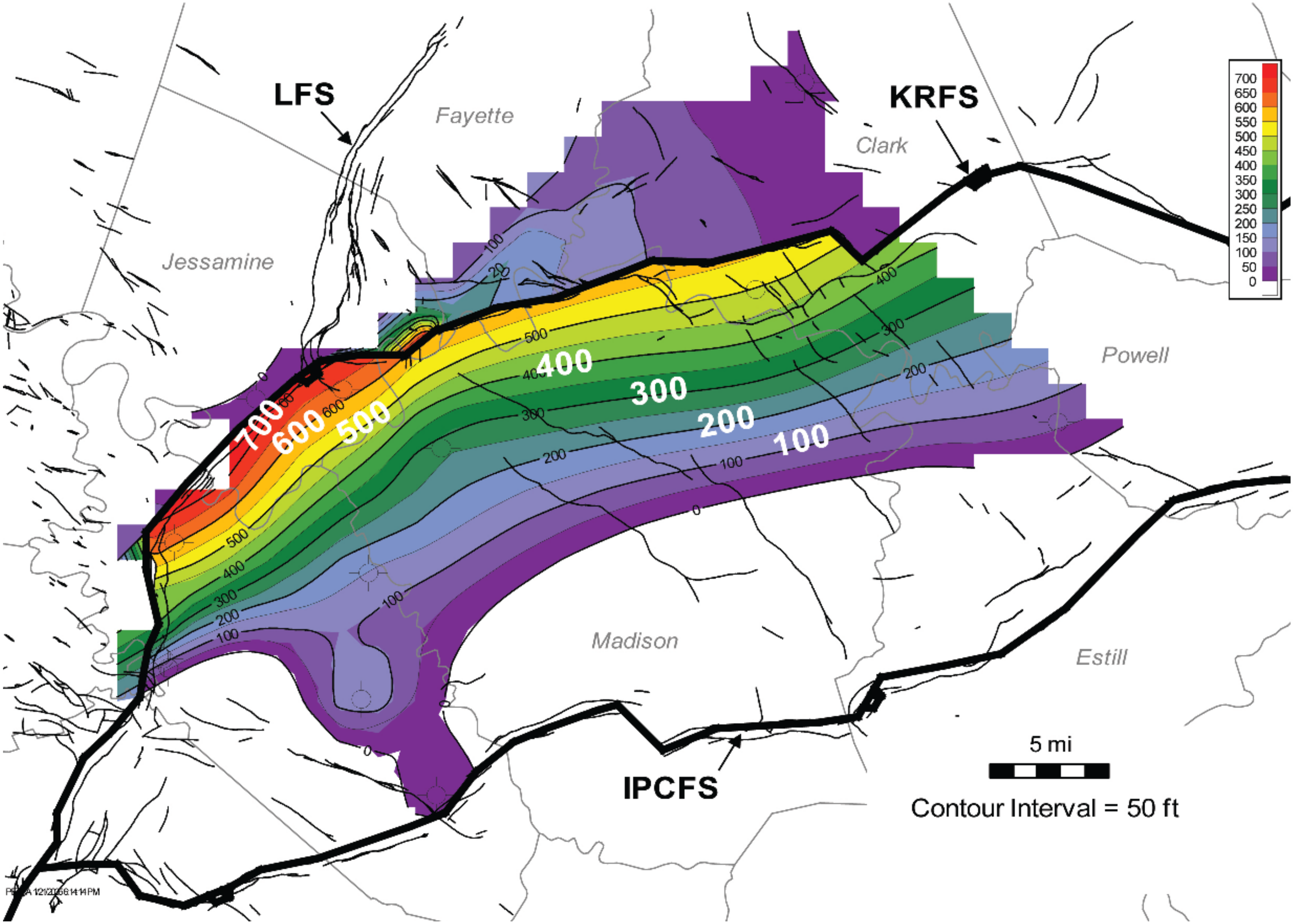

Figure 4.14. Thickness of sandstones in the Rome Formation near the intersection of the Kentucky River Fault System (KRFS) and Irvine–Paint Creek Fault System (IPCFS) with the Lexington Fault System (LFS) on the northwestern margin of the Rome Trough. After Harris and others (2004). The entire thickness is not porous or permeable. The thickness shown is the thickness of the entire interval.

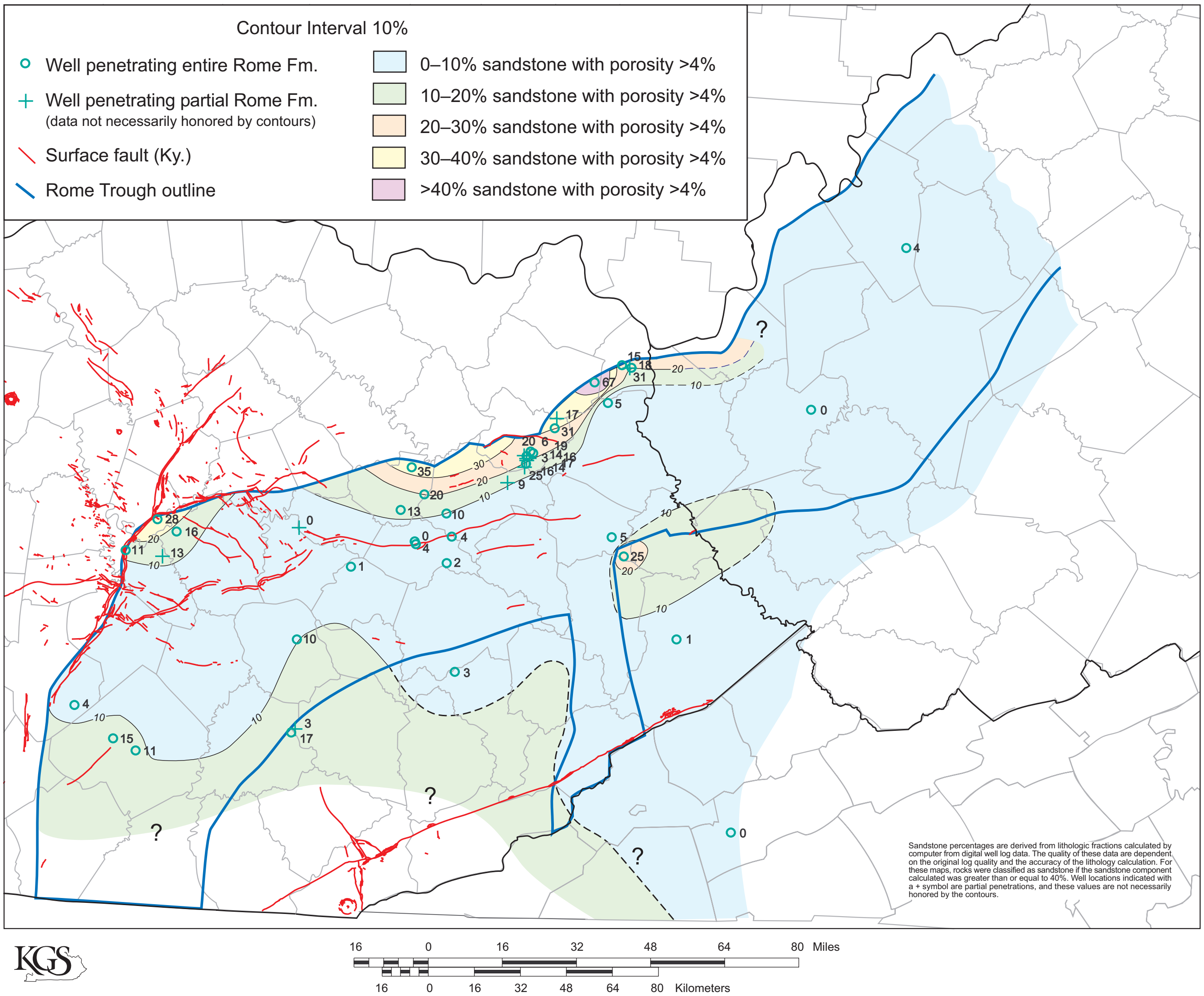

Figure 4.15. Rome Formation net sandstone percentage, showing the narrow belt of thick sandstones along the northern margin of the Rome Trough. From Harris and others (2004).

to increase hydrocarbon flow from the reservoir to the well. The sand had average pump rates of 8.6 bbl/min at 4,900 psi (Rodvelt and others, 1999). This well demonstrates that at least small amounts of liquid CO_2 can be injected into the Rome sandstones.

Overlying Sealing/Confining Units. The primary confining interval for Rome sandstones will be the overlying Conasauga Group where it is not faulted. Relatively few wells have penetrated this unit, so leakage up old wellbores should not be a major issue. Secondary seals would be the Knox Group and Middle Ordovician (Black River–Trenton) carbonates (Fig. 4.5). The ultimate seal would be the Upper Ordovician shales in the eastern part of the Rome Trough, but that interval occurs at the surface in the western part of the trough. The stratigraphically higher Devonian shale would also be an ultimate confining interval in the eastern part of the trough.

One issue that will need further research is the sealing properties of faults that bound or are in close proximity to potential Rome sandstone reservoirs. The thickest Rome sandstones are adjacent to the Kentucky River Fault System. These faults and others were active during Rome sandstone deposition. Many smaller faults extend upward into at least the Conasauga Group (the overlying seal). As potential pathways for fluid migration, faults near any proposed injection site will need to be investigated to see if they are conductive or

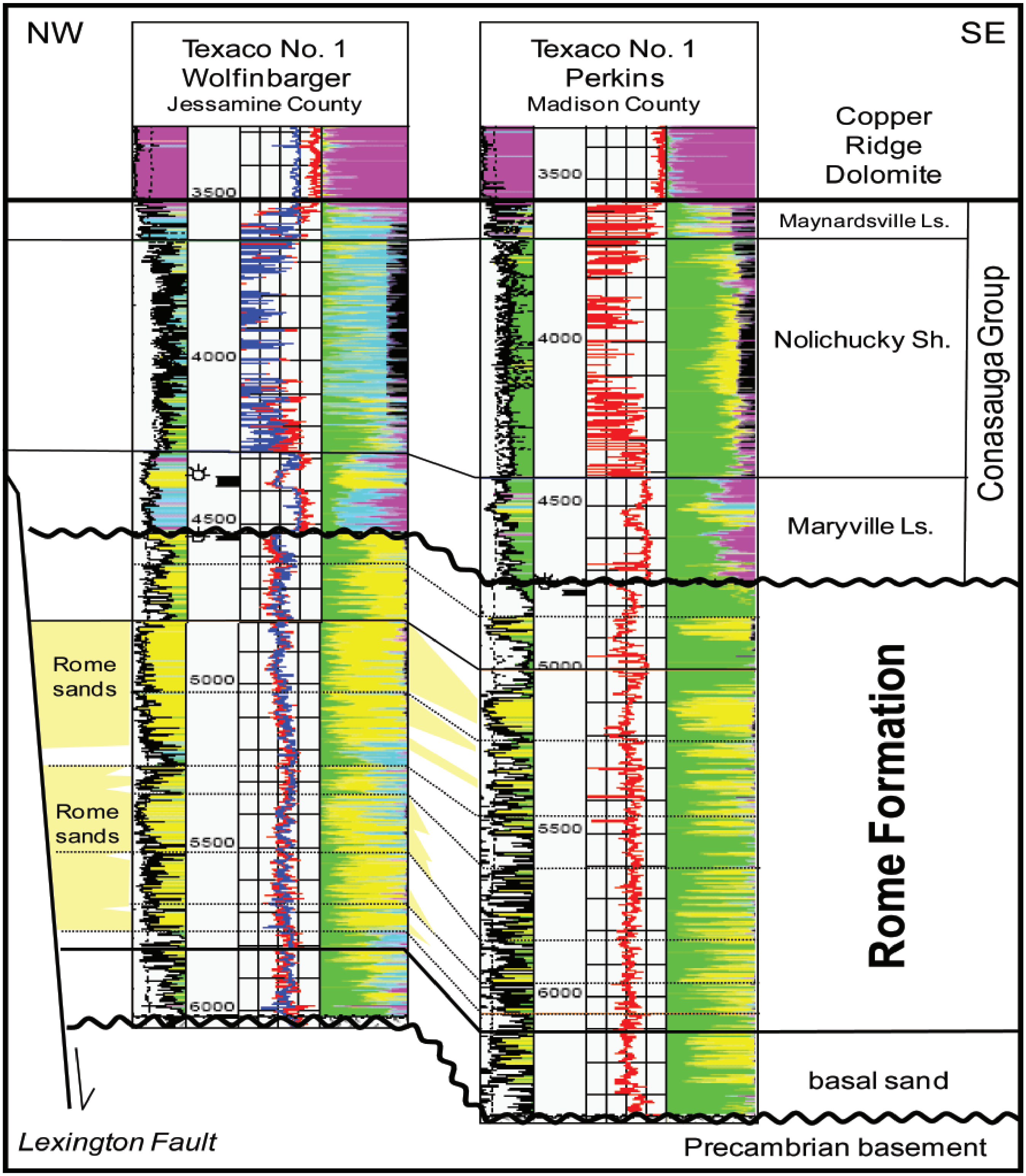

Figure 4.16. Geophysical log profiles of the Rome Formation showing thickening across the Lexington Fault System on the west end of the Rome Trough, and the concentration of thick Rome sandstones toward the fault. Modified from Hickman and Harris (2004, Plate 7B, dip section 4). The entire interval of sandstones is not porous, and only a smaller part of the interval shown might be suitable as a reservoir or reservoirs. Colors for gamma (left side) and density-neutron (right side) are shaded to represent shale-dominated (green), sandstone-dominated (yellow), limestone-dominated (blue), and dolomite-dominated (pink) zones. Datum is top of Conasauga Group.

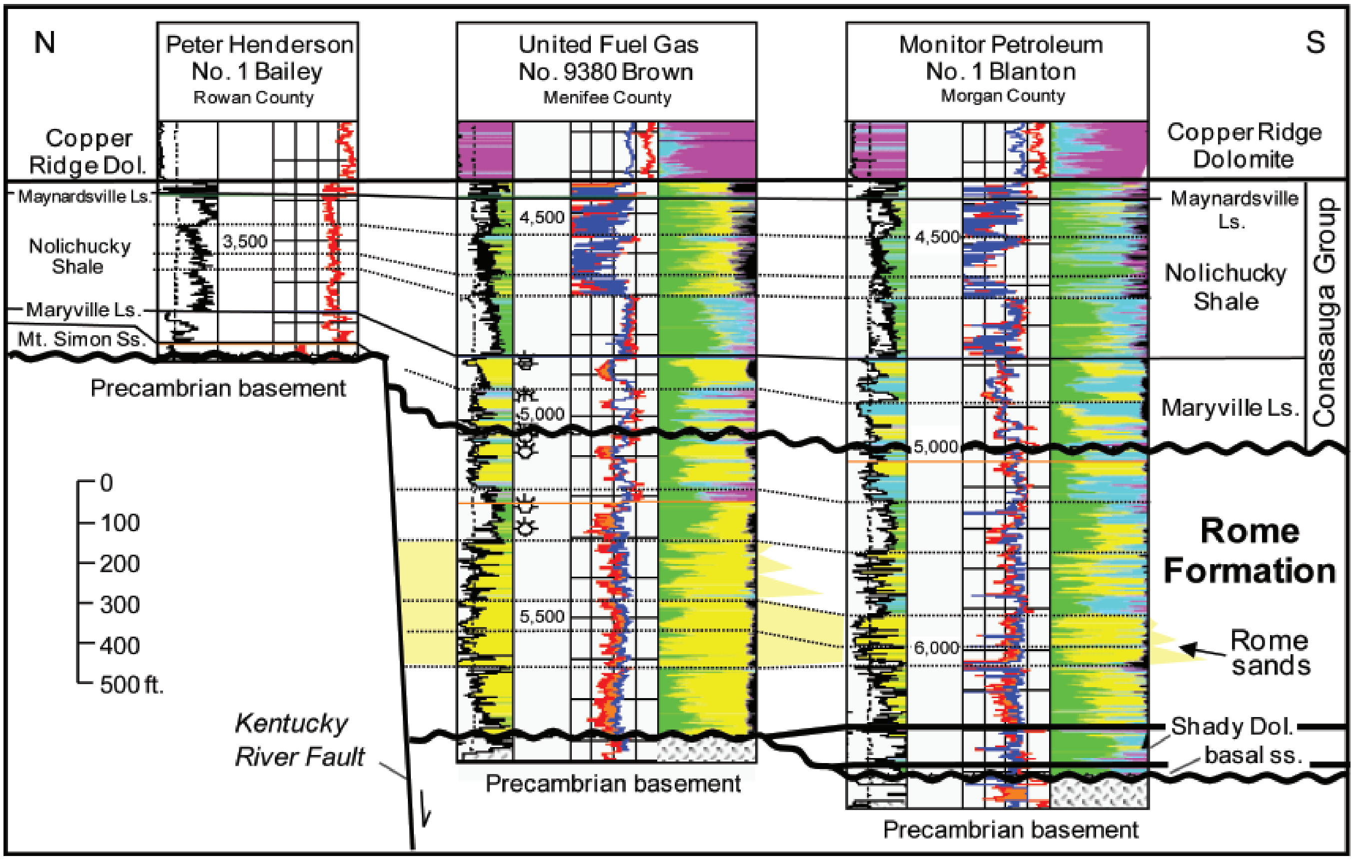

Figure 4.17. Geophysical log profiles of the Rome Formation showing thickening across the Kentucky River Fault System on the northern margin of the Rome Trough, and the concentration of thick Rome sandstones toward the fault. The Mount Simon Sandstone outside of the trough is relatively equivalent to the Maryville Limestone of the Conasauga Group. Modified from Hickman and Harris (2004, Plate 7B, dip section 4). Colors for gamma (left side) and density-neutron (right side) are shaded to represent shale-dominated (green), sandstone-dominated (yellow), limestone-dominated (blue), and dolomite-dominated (pink) zones. Datum is top of Conasauga Group. Dol = Dolomite. Ls = Limestone. ss = sandstone (informal). Ss = Sandstone (formal).

sealing. Using areas of structural closure to levels that do not intersect faults may be another way to use thick Rome sandstones as carbon storage reservoirs, so that the faults would not need to be tested, although this would likely limit reservoirs to much smaller sizes.

CO_2 Storage Potential. Rome sandstones cover an area of 13,157 mi^2 in eastern Kentucky, and were calculated to have potential volumetric storage capacity of 11 billion short tons (10 billion metric tons) (Wickstrom and others, 2005). If only 10 percent of that volume is accessible, there would be 1.1 billion short tons (1.0 billion metric tons) of storage; if 1 percent is accessible, then 0.1 billion short ton of storage would be available. These estimates might be further reduced because of current gas production and leases, unless CO_2 was used for secondary recovery. In most cases, Rome sandstones have less than 10 percent porosity, so that injectivity may also be a concern for large-volume storage. All of the Rome sandstones occupy a narrow belt that is bounded and cross-cut by faults.

Conasauga Group (Nonsandstone)

CO_2 unit type: primary or secondary confining unit (seal)
KGS stratigraphic code: 375CNSG, 375NCCK, 375MRVL, 375RGRV, 375RLDG, 375PPKV
Series/system: Cambrian
Thickness: 325–5,000 ft
Distribution: eastern Kentucky
Number of wells with completion: 0
Number of wells that TD: 8
Approximate number of wells drilled through unit: 94

Interval Definition. The Conasauga Group includes strata from the top of the Rome Formation to the base

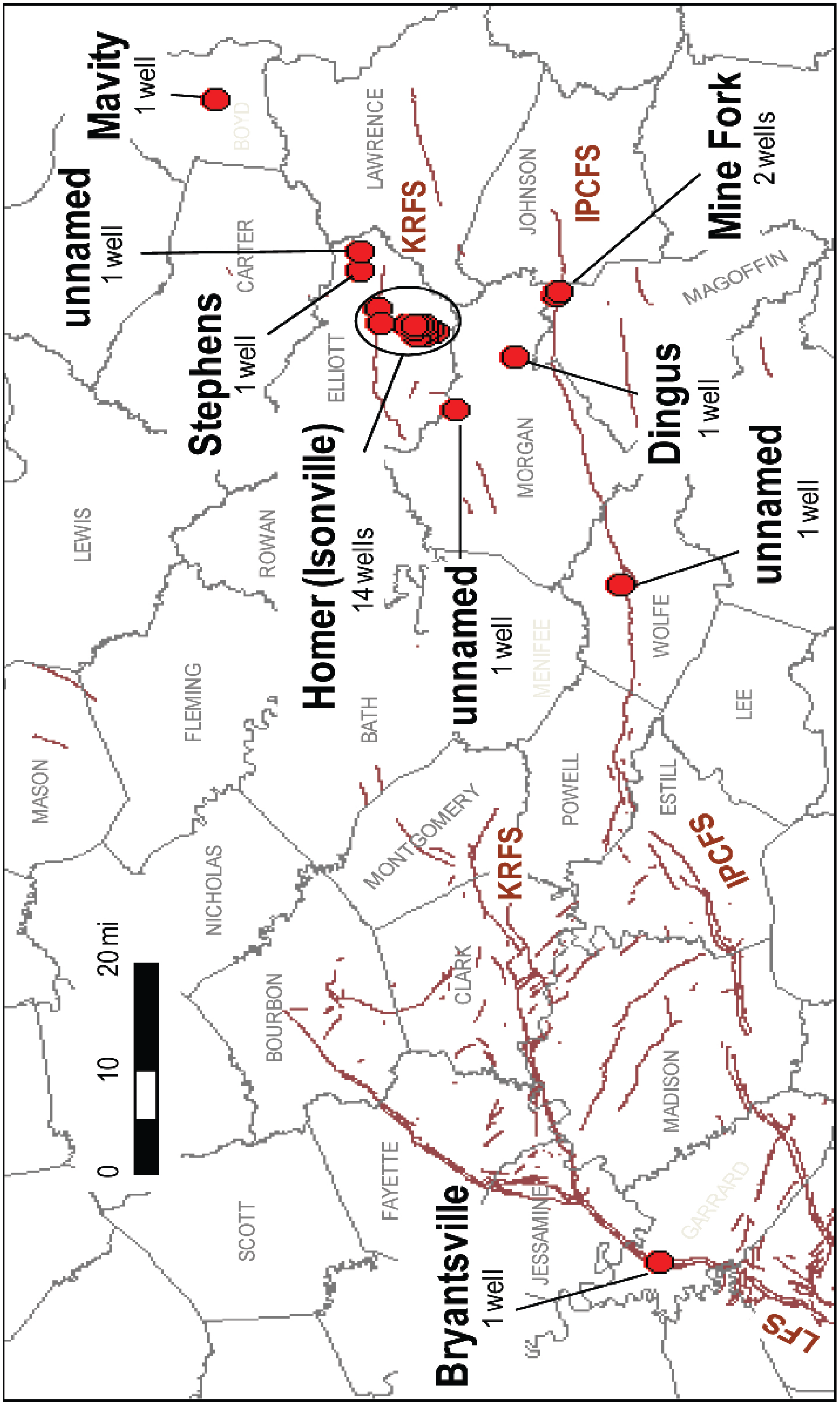

Figure 4.18. Locations of wells and fields with recorded completions (show or production) in the Rome sandstones. Trace of surface faults shown in brown. KRFS=Kentucky River Fault System. IPCFS=Irvine–Paint Creek Fault System. LFS=Lexington Fault System.

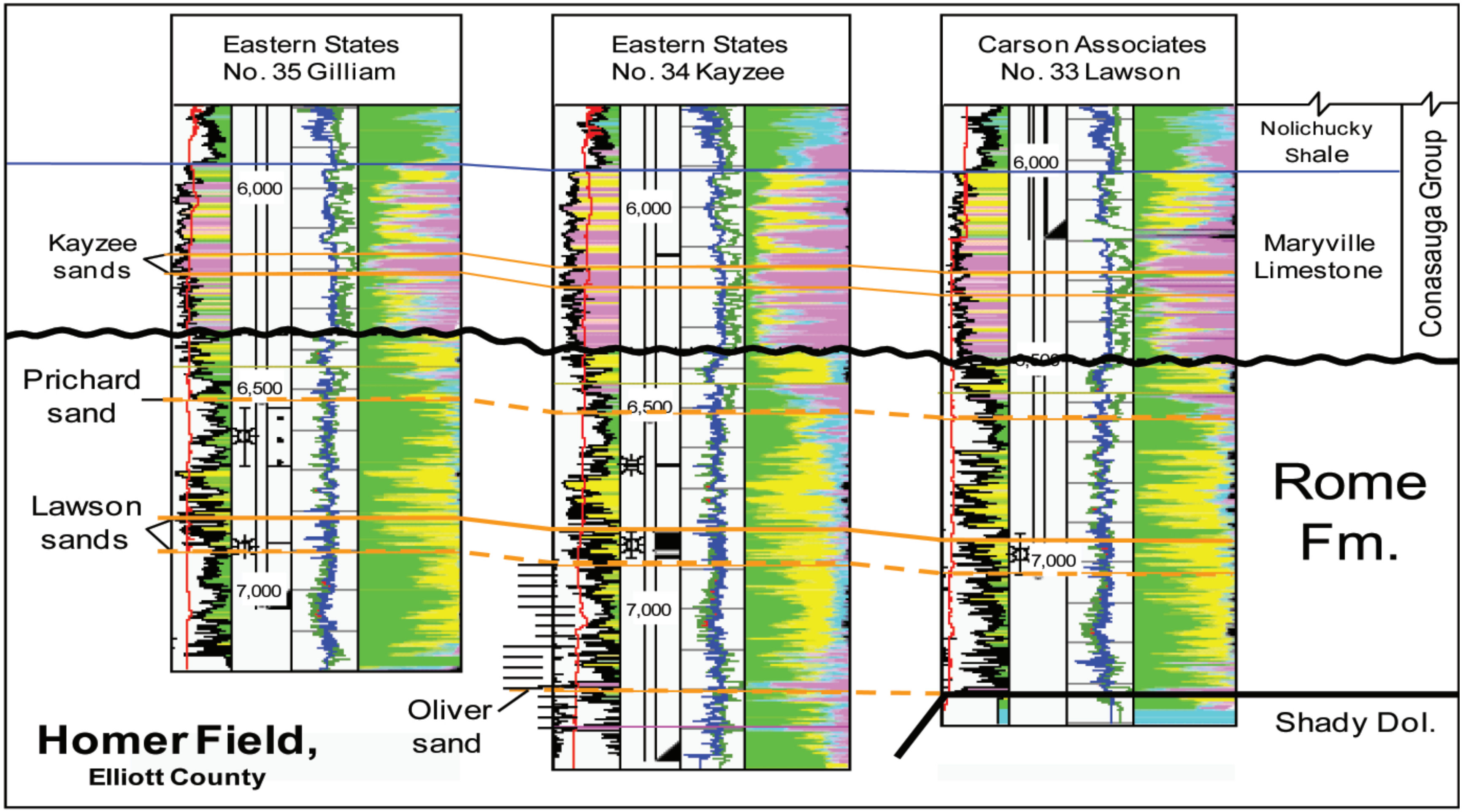

Figure 4.19. Geophysical log profiles through the Homer Field, Elliott County, showing informally named drillers' sands in the Rome Formation and overlying Maryville Limestone. Modified from Hickman and Harris (2004, Fig. 6-4). See Figure 4.18 for field location. Colors for gamma (left side) and density-neutron (right side) are shaded to represent shale-dominated (green) and sandstone-dominated (yellow) zones. Dol = Dolomite.

of the Copper Ridge (lower Knox) Dolomite in eastern Kentucky (Figs. 4.4–4.5). The Conasauga Group consists of the following formations, in ascending order: Pumpkin Valley Shale, Rutledge Limestone, Rogersville Shale, Maryville Limestone, Nolichucky Shale, and Maynardville Limestone. The lower three units are restricted to the Rome Trough, whereas north of the trough, the Maryville Limestone forms the base of the Conasauga and unconformably overlies the Rome Formation (Figs. 4.4–4.5) (Harris and others, 2004). The Conasauga as discussed in this report follows its formal stratigraphic definition, except that sandstones in the Maryville Limestone are treated separately.

The upper Maryville Limestone, Nolichucky Shale, and Maynardville Limestone are laterally equivalent to the Eau Claire Formation in central and western Kentucky (Harris and others, 2004). The boundary between the Eau Claire and Conasauga is placed in the area where the Conasauga thins and the Maynardsville Limestone pinches out. Current well control is not sufficient to precisely show this boundary, so it is shown as a sawtoothed color break in Figure 4.20. In south-central Kentucky, the boundary between the two units is herein placed at the Lexington Fault System on the western edge of the Rome Trough.

General Description. The Conasauga consists of shales, siltstones, limestones, and sandstones. Summaries of units within this interval are provided in Ryder (1992) and Ryder and others (1996, 1997) and Harris and others (2004). Descriptions of samples from 10 eastern Kentucky wells can be found in McGuire and Howell (1963). The Conasauga Group has thicknesses of 338 to 4,079 ft, measured in subsurface logs, although it may be more than 5,000 ft thick in some parts of the Rome Trough based on seismic analyses. The Conasauga is less than 1,000 ft thick north of the Kentucky River Fault System, thickens to more than 3,000 ft south of the Irvine–Paint Creek Fault System, and is more than 5,000 ft thick in the center of the Rome Trough (Figs. 4.21–4.22). South of the Rome Trough, the Conasauga is generally 1,000 to 3,000 ft thick. Measured thicknesses from logs of individual formations within the Conasauga are: Pumpkin Valley Shale, 0 to 473 ft thick; Rutledge Limestone, 0 to 454 ft thick (may be more than 1,000 ft); Rogersville Shale, 0 to 1,130 ft thick; Maryville Limestone, 65 to 2,311 ft thick; Nolichucky Shale, 149 to 1,241 ft thick; and Maynardsville Limestone, 23 to 212 ft thick. All of the individual units thicken into the trough (Fig. 4.21), because the trough was actively subsiding during deposition. The lower three units are confined to the trough,

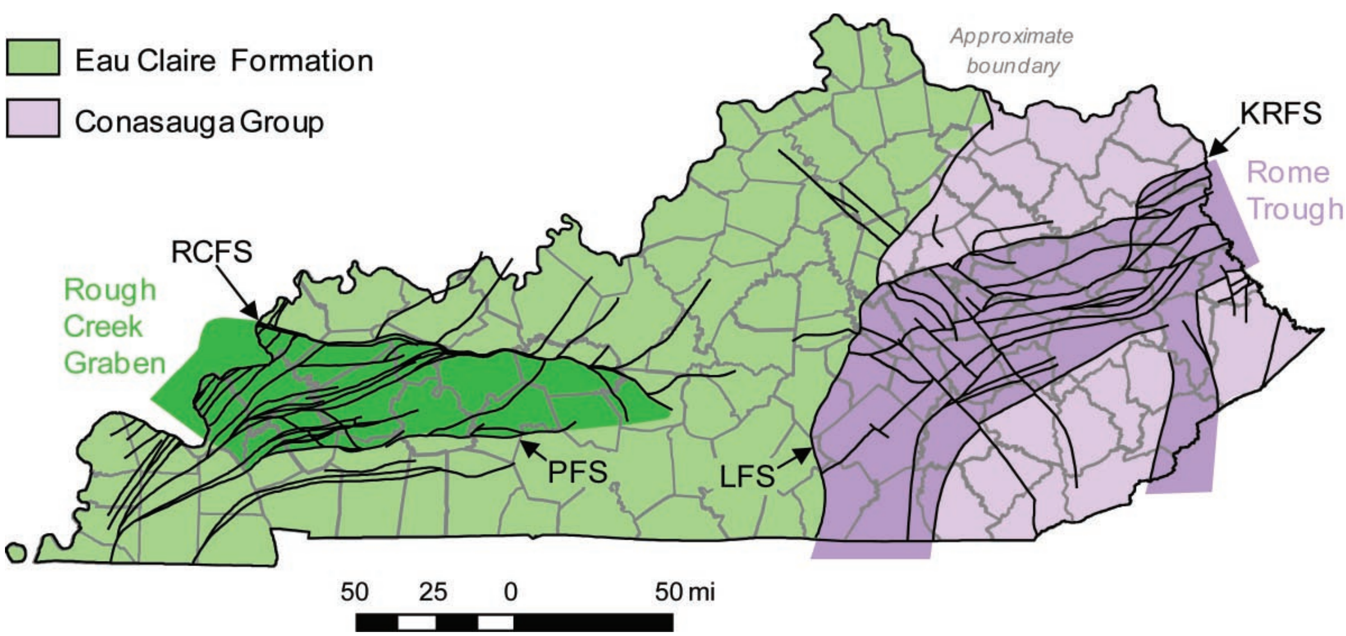

Figure 4.20. Distribution of the Eau Claire and Conasauga Formations. The boundary between the formation in northeastern Kentucky follows the suggestion of Harris and others (2004). Basement grabens are shaded darker. KRFS = Kentucky River Fault System. LFS = Lexington Fault System. PFS = Pennyrile Fault System. RCFS = Rough Creek Fault System.

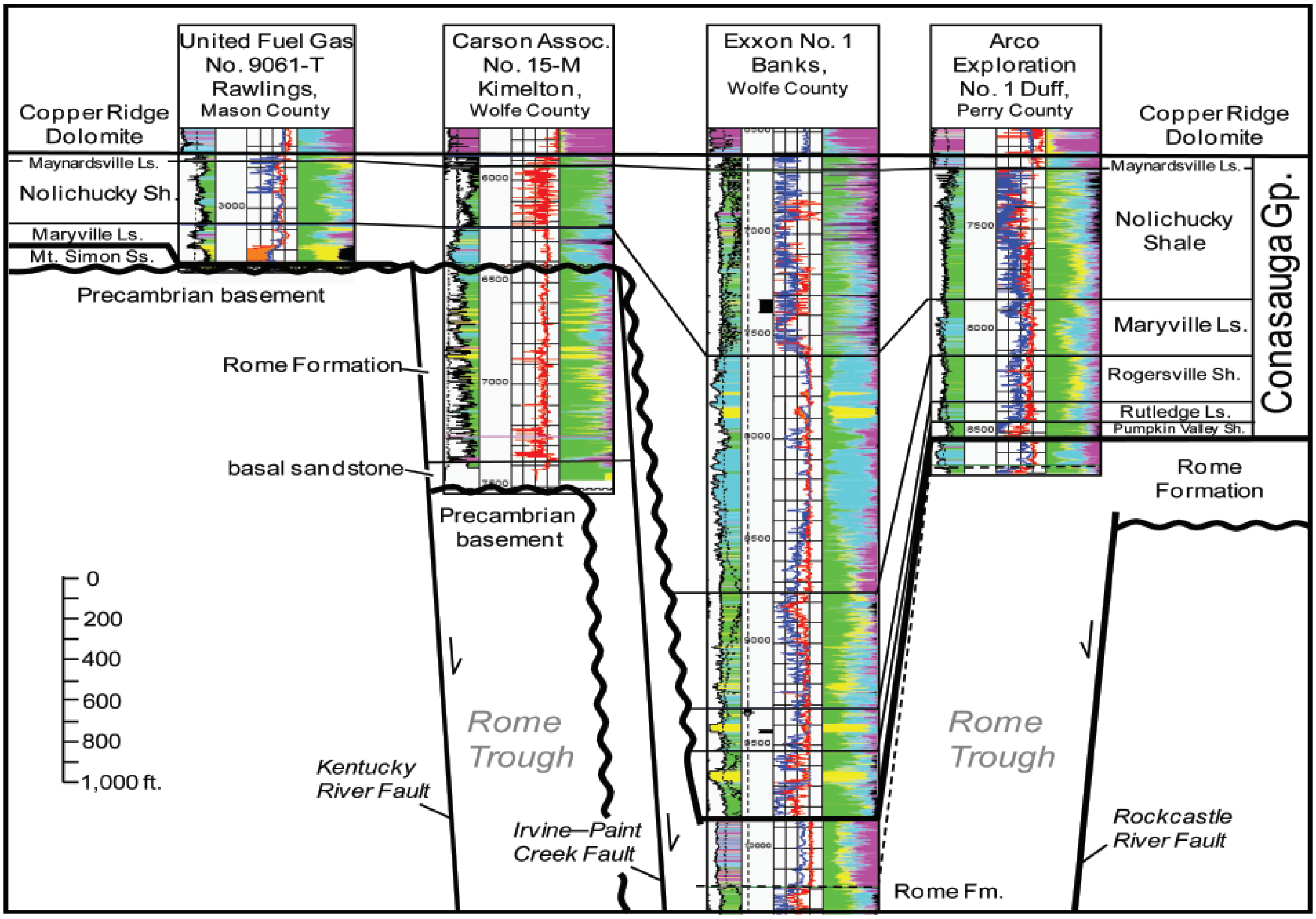

Figure 4.21. Geophysical log profiles of the Conasauga Group across the Rome Trough showing thickness and distribution changes of the formations that comprise the group. Modified from Harris and others (2004, Plate 7A, dip section 4). Colors for gamma (left side) and density-neutron (right side) are shaded to represent more limestone-dominated (blue), dolomite-dominated (pink), shale-dominated (green), and sandstone-dominated (yellow) zones. Datum is top of Conasauga Group. Fm = Formation. Ls = Limestone. Sh = Shale. Ss = Sandstone.

but the upper three units extend beyond the trough and their thicknesses vary less, suggesting less fault movement during the latter stages of Conasauga deposition.

The contact of the Pumpkin Valley Shale with the underlying upper limestone of the Rome Formation is sharp. The Pumpkin Valley consists of gray shale, siltstone, and thin sandstones (Fig. 4.21) (Ryder, 1992; Harris and others, 2004). The overlying Rutledge Limestone is dominated by micritic limestone with lesser amounts of sandy limestone and sandstone (Ryder, 1992; Harris and others, 2004).

The Rogersville Shale consists of silty red and green shales and micritic limestones, which grades north and west into sandy shales (Ryder, 1992; Ryder and others, 1996, 1997; Harris and others, 2004). The Rogersville Shale is conformably overlain by the Maryville Limestone in the deeper parts of the Rome Trough. Out of the trough to the north and west, however, the Rogersville and underlying Conasauga units are truncated such that the base of the Maryville Limestone becomes the base of the Conasauga Group (Figs. 4.16–4.17, 4.19).

The Maryville Limestone is a thick sequence of argillaceous limestone and limestone that interfingers to the east in West Virginia, and south in Tennessee with the Elbrook/Honaker Dolomite. The Maryville may contain a 50- to 300-ft-thick sandy interval in its lower half within the Rome Trough (Ryder and others, 1997).

The Maryville Limestone is overlain by the Nolichucky Shale, which is dominated by calcareous, olive green to gray, silty shales and siltstones (Elton and Haney, 1974). The overlying Maynardsville Limestone is a micritic to coarse-grained limestone (Webb, 1980).

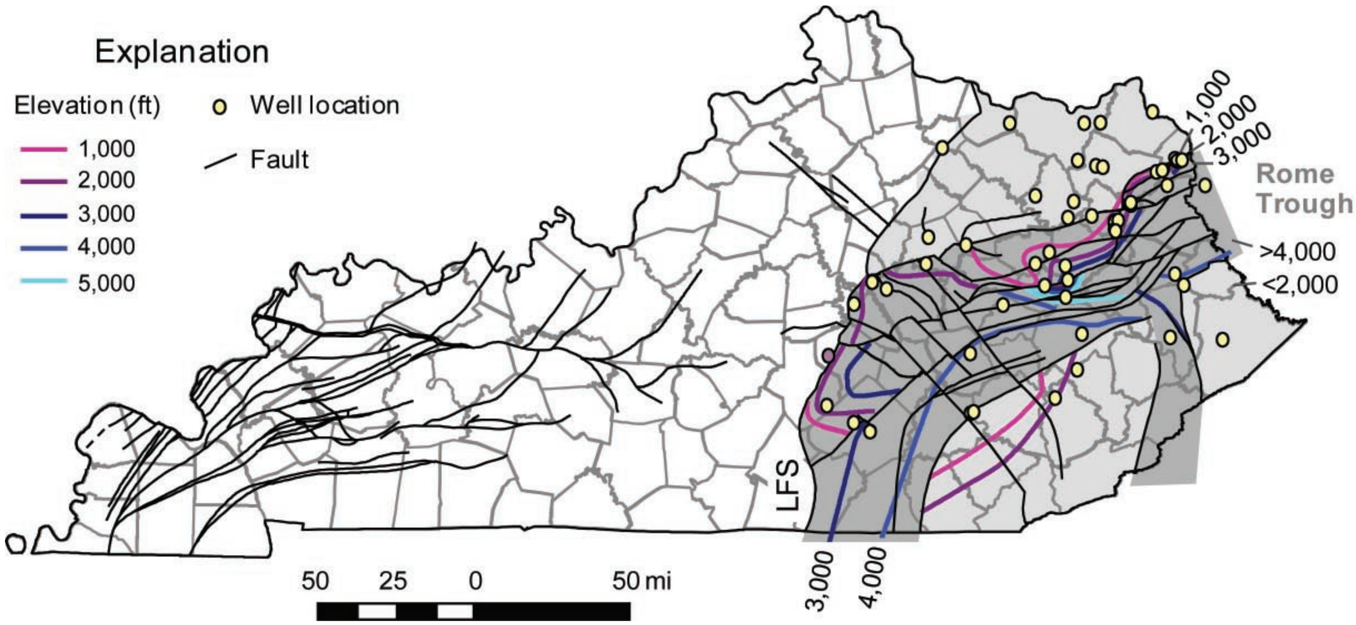

Figure 4.22. Thickness of the Conasauga Group in eastern Kentucky (shaded gray). Partly equivalent Eau Claire Formation in western Kentucky is not shown and is discussed separately.

The contact between the Maynardsville and overlying Copper Ridge Dolomite of the Knox Group is sharp.

Within the Conasauga, the Rutledge and Maryville Limestones generally thin to the west and southwest, laterally grading into the surrounding shales. Toward the southern margin of the trough and southward into southeastern Kentucky, the Conasauga is composed almost entirely of shale, and the individual formations recognized to the north cannot be delineated below the Maynardsville Limestone. The term "Conasauga Shale," rather than Conasauga Group, was suggested by Harris and others (2004) for areas where individual formations cannot be distinguished within the group.

The Conasauga is not exposed at the surface in Kentucky. It is shallowest (2,500 ft deep; –2,000 ft below sea level) above the Grenville Front (Lexington Fault System) in northern Kentucky, and is more than 10,800 ft deep (–10,000 ft below sea level) in southeastern Pike County (Fig. 4.23). Structural relief at the top of the Conasauga is less, compared to underlying strata (e.g., basal sandstone; Fig. 4.11), signifying diminished fault influence during the latter stages of Conasauga deposition.

Known Reservoirs or Types of Porosity. Aside from sandstones in the Maryville Limestone, the Conasauga has no known production and exhibits little porosity. Thick shales in this interval, especially toward the south, should provide adequate confinement for underlying units where the shales are not faulted. Also, analyses of dark shales in the Rogersville Shale from West Virginia yielded high total organic carbon values (1.2 to 4.0 percent), which indicates that this may be a source rock for Cambrian and Ordovician oil and gas (Ryder and others, 2005). The organic matter in the Rogersville may provide a preferential adsorption mechanism for CO_2. Adsorption would enhance the sealing properties of these rocks if they were used as a confining interval, provided the organic contents were high enough in a thick and laterally continuous interval of the unit.

Overlying Sealing/Confining Units. Shales and limestones in the Conasauga Group all have low porosity, and therefore should provide an adequate seal for potential underlying reservoirs. What effect, if any, faults will have on sealing properties in this unit, is not clear at this time. If porosity is found in any Conasauga unit, the overlying formation within the group would be the primary sealing interval. Thick, overlying Knox and Middle and Upper Ordovician (Black River–Trenton) carbonates would form secondary seals (Fig. 4.5). The ultimate seal would be the Upper Ordovician shale interval.

CO_2 Storage Potential. Overall, limestones and shales of the Conasauga Group have little or no porosity and

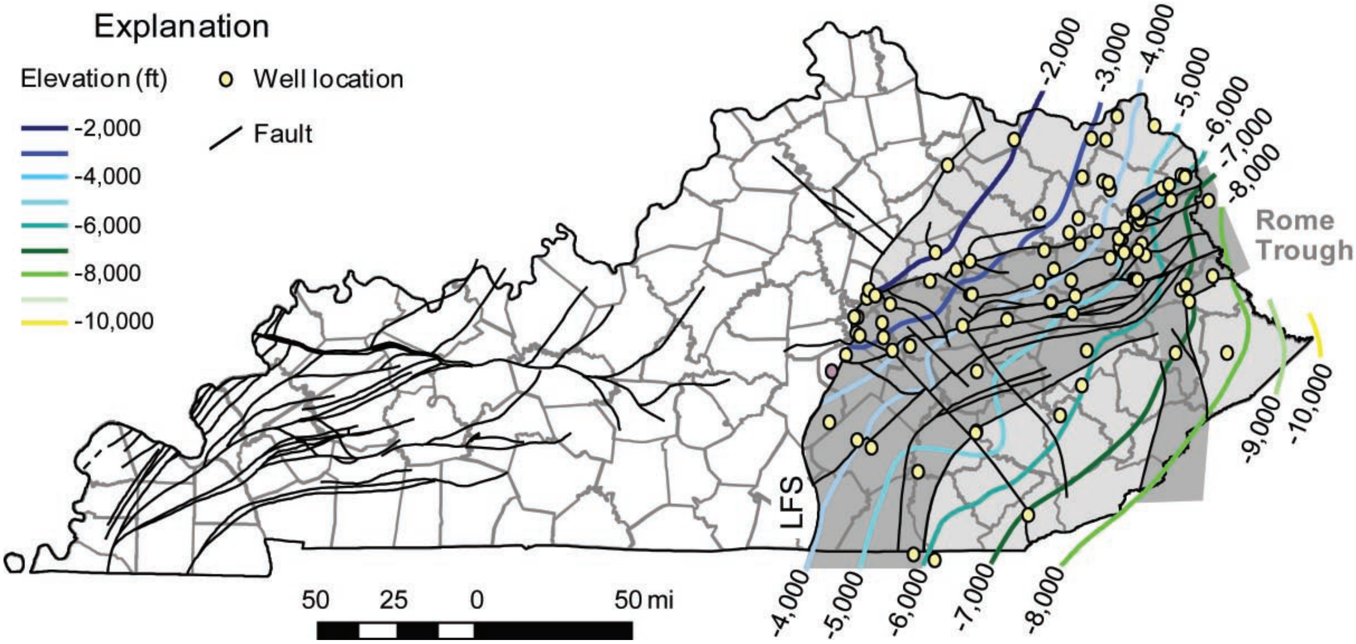

Figure 4.23. Structural elevation on top of the Conasauga Group (gray background). LFS = Lexington Fault System. Datum is sea level.

are therefore considered seals or confining intervals, with little or no carbon storage potential.

Maryville Sandstones (Conasauga Group)

CO_2 unit type: potential local reservoir
KGS stratigraphic code: 375MRVL (for entire Maryville, not just sandstone)
Series/system: Cambrian
Thickness: 0–25 ft
Distribution: northeastern Kentucky
Number of wells with completion: 2
Number of wells that TD: 8?
Approximate number of wells drilled through unit: 94

Interval Definition. Harris and others (2004) analyzed and mapped sandstones in the Maryville Limestone of the Conasauga Group (Figs. 4.4–4.5), and found the sandstones concentrated in (1) a small area near the northwestern corner of the Rome Trough in parts of Jessamine and Garrard Counties and (2) a broader area in parts of Menifee, Elliott, and Rowan Counties (Fig. 4.24). The second depocenter extends out of the trough, northward into Ohio (Harris and others, 2004). In Elliott County the sandstones are called the "Kayzee sand" by drillers.

General Description. Sandstones in the Maryville Limestone are quartzose and generally quartz- or carbonate-cemented (McGuire and Howell, 1963). The Kayzee sandstones of Elliott County are each 10 to 15 ft thick and are separated by 40 to 65 ft of shale and carbonates (Fig. 4.25) (Hickman and Harris, 2004). One of these sandstones may represent the lateral equivalent of the Mount Simon Sandstone to the west (Figs. 4.17, 4.21).

Known Reservoirs or Types of Porosity. Maryville sandstones (i.e., Kayzee) have produced gas in the Homer Field (previously Isonville Pool) of Elliott County (Figs. 4.18–4.19, 4.25). The Carson Associates No. 1 Ray well also produced gas and condensate from the Conasauga Group (Maryville Limestone) in Lawrence County (Harris and others, 2004). The discovery well in the Homer Field had an estimated initial open flow of 11,000 ft^3/day, but the reservoir was damaged from a blowout and subsequent use of a saline "kill" fluid. Log porosities in the field range from near 0 to 12 percent. Production is from a structural trap related to faulting along the northern margin of the Rome Trough, similar to production in the underlying Rome sandstones. Production depths are 6,109 to 7,026 ft (Fig. 4.25). Because the distribution of the sandstones in the Maryville Limestone and Rome sandstones is similar, there may be opportunities for encountering reservoirs in both intervals in parts of Jessamine, Garrard, Madison, Menifee, Morgan, and Elliott Counties.

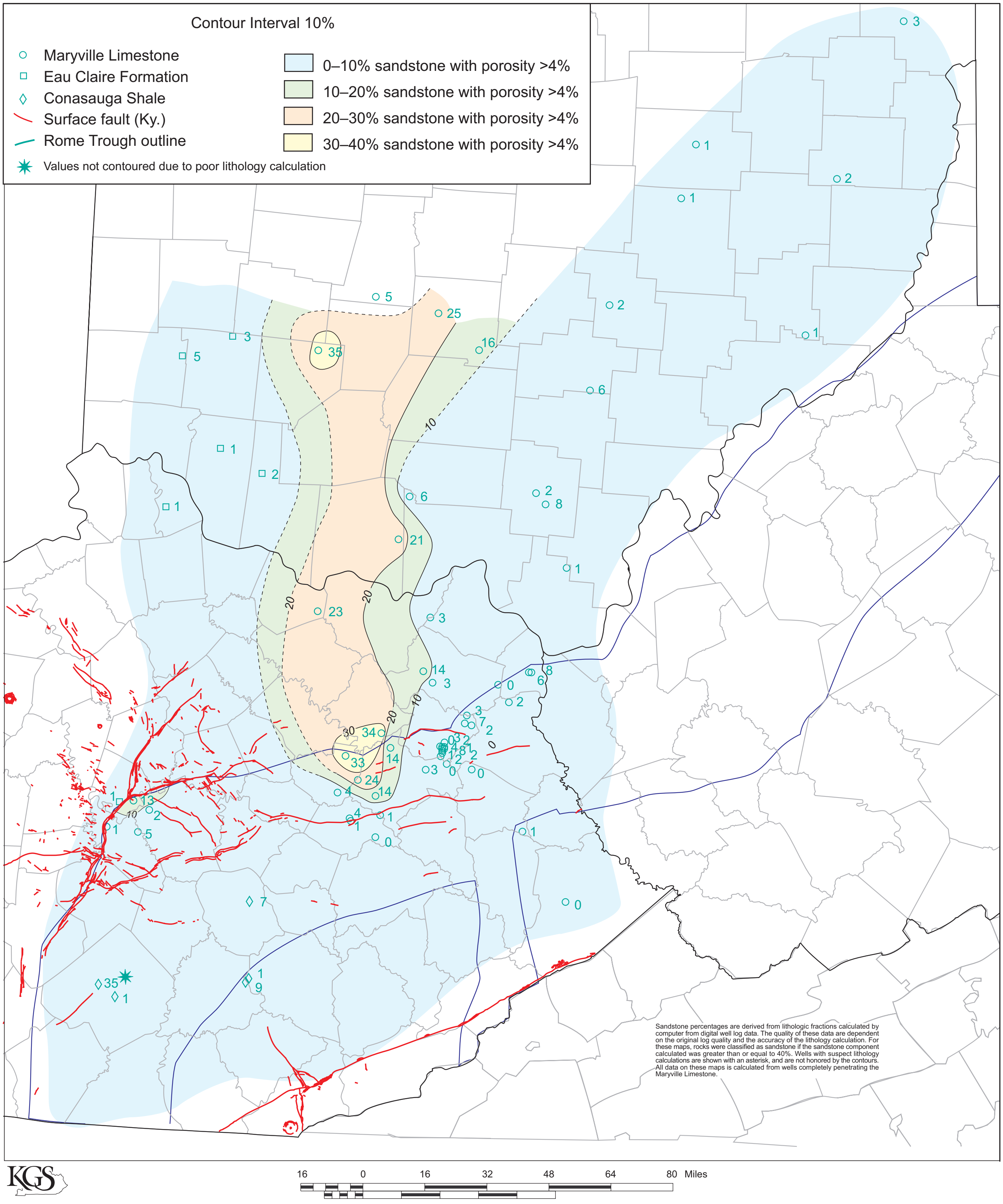

Figure 4.24. Sandstone distribution pattern in the Maryville Limestone, Conasauga Group. From Harris and others (2004).

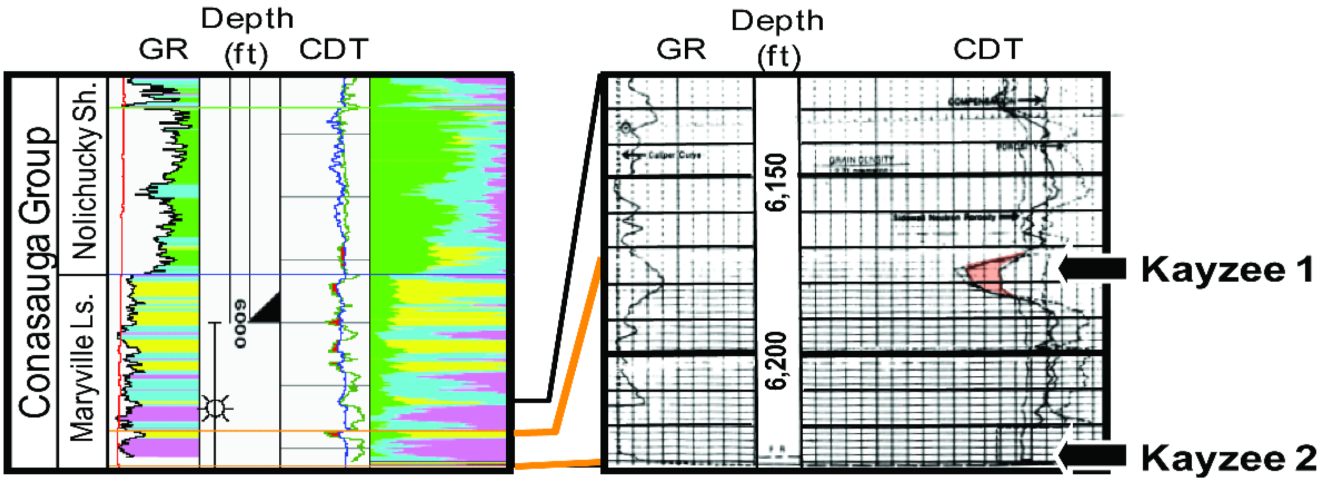

Figure 4.25. Geophysical log through the Kayzee sands in the Homer Field of Elliott County. In the log on the left, colors for gamma (left side) and density-neutron (right side) are shaded to represent more limestone-dominated (blue), dolomite-dominated (pink), shale-dominated (green), and sandstone-dominated (yellow) zones. The Kayzee sands are the two yellow lines toward the bottom of the well. In the expanded view, porosity in the upper Kayzee sand is shown in red. Ls = Limestone. Sh = Shale.

Overlying Sealing/Confining Units. The immediate confining interval for porous sandstones in the Maryville Limestone would be overlying low-porosity carbonates and shales in the Maryville, and overlying formations of the Conasauga Group. The shales and carbonates should form adequate seals where they are unfaulted. Relatively few wells have penetrated Maryville sandstones, so there should be few, if any, issues of leakage up old wellbores. Thick, overlying Knox and Middle and Upper Ordovician (Black River–Trenton) carbonates would form secondary seals (Fig. 4.5).

CO_2 Storage Potential. The Conasauga sandstones are unlikely to have large storage potential, although they may be important reservoirs locally in northeastern Kentucky. Aristech Chemical Corp. operated a Class 1 injection well into the Maryville sandstones at a depth of 5,514 ft in Scioto County, Ohio, just across the Ohio River from Greenup County, Ky. According to EPA's Ohio Class 1 well data (Ohio EPA, no date), the plant injected 1.18 million gal of organic chemicals (classified as hazardous liquids) during its operation. More data on this well would be useful for determining the equivalent volume of CO_2 that could have been injected. The area of known porosity in the Conasauga sandstones is approximately 25 mi^2, and it was calculated to have potential volumetric storage capacity of 16 million short tons (15 million metric tons) in the phase I report of the Midwest Regional Carbon Sequestration Partnership (Wickstrom and others, 2005). If 10 percent of that volume is ultimately accessible for storage, capacity would be 1.6 million tons (1.5 million metric tons); if 1 percent, then capacity would equal 0.16 million short ton (0.15 million metric ton). The volumes might be further reduced in order to account for gas production and leases unless CO_2 was used for secondary recovery.

Basal Sandstone (Western Kentucky)

CO_2 unit type: potential regional reservoir
KGS stratigraphic code: 375BASAL, 375ARKS
Series/system: Cambrian
Thickness: 0–1,942 ft
Distribution: western Kentucky (Rough Creek Graben)
Number of wells with completion: 0
Number of wells that TD: 2
Approximate number of wells drilled through unit: 0

Interval Definition. Sandstones that directly overlie the Precambrian unconformity are generally overlain by a sandstone, but in Kentucky, sandstones above the unconformity (Figs. 4.4–4.5, 4.9) in different areas can have different characteristics and ages. The sandstone north of the Rome Trough and Rough Creek Graben is called the Mount Simon Sandstone, whereas the sandstone that occurs above the Precambrian unconformity south of the Rough Creek and Kentucky River Fault Systems is informally called the basal sandstone. The sandstones do not appear to be the same unit. In western Kentucky, the Exxon No. 1 Jimmy Bell and Conoco No. 1 Turner well in Webster and McLean Counties, respectively (red circles in Figs. 4.10–4.11), encountered thick sandstones south of the northernmost fault in the Rough Creek Fault System (Figs. 4.26–4.27). North of the faults, the Mount Simon Sandstone pinches out, so sandstones south of the fault are not connected to the Mount Simon and are likely not equivalent. Basal sandstones south of the faults are herein interpreted as a basal (non-Mount Simon) sandstone. The western Kentucky basal sandstone occupies a stratigraphic position similar to the Rome and basal sandstones in eastern Kentucky (Figs. 4.5, 4.9), but stratigraphic equivalence or connections between the two are unlikely. The southern extent of the basal sandstone in western Kentucky is uncertain because no wells are deep enough to have penetrated it in the graben or on the shelf south of the graben. A basal sandstone is not recognized in western Tennessee (see, for example, Whitaker and others, 1992), so the southern margin is likely in Kentucky, and possibly confined to the Rough Creek Graben.

General Description. Twenty sidewall cores from the thick sandstone in the Conoco No. 1 Turner well of McLean County (middle well in Figure 4.26) were described in a technical service report by Mitchell (1993). The basal sands in this well are very fine- to medium-grained, well to poorly sorted, and calcite-cemented. Framework grains are dominated by quartz (50 percent or more) and feldspar (4 to 6 percent), but volcanic rock fragments are abundant, and skeletal carbonates also occur. Some samples are glauconitic. Pore-filling materials include cements such as quartz overgrowths, calcite and chlorite, and shaly pseudomatrix, which formed at multiple times during diagenesis (Mitchell, 1993). The abundance of volcanic fragments is different from typical Mount Simon Sandstone, which tends to support the hypothesis that this sandstone (or series of sandstones) is distinct from the Mount Simon, which tends not to have abundant rock fragments.

Little can be determined about thickness trends for the basal sandstone in western Kentucky because only two wells penetrate the interval (Figs. 4.10–4.11). The thickness of this interval in the two wells suggests, however, that synsedimentary fault movement along the northern margin of the graben accompanied sand deposition, similar to development of the Rome sandstones in eastern Kentucky. The deep burial of the basal sandstone will require more seismic analysis to help determine its distribution in other parts of the Rough Creek Graben. Available seismic data are currently being investigated by the Rough Creek Graben Consortium, a Kentucky Geological Survey research project with industry. This research should yield a better understanding of the distribution and thickness of basal sandstones in parts of western Kentucky.

Known Reservoirs or Types of Porosity. There is no known production from the basal sandstone in western Kentucky, and in both wells that have penetrated the sandstone, the sandstone showed little to no porosity. The abundance of rock fragments and pseudomatrix in the basal sandstone would also tend to indicate low probabilities of encountering significant porosity with depth.

Overlying Sealing/Confining Units. In western Kentucky, if suitable porosity is ever found in the basal sandstones, the thick shales and dense carbonates of the overlying Eau Claire Formation would be the primary seal where the unit is unfaulted (Fig. 4.5). One possible effect of faulting is demonstrated in the Exxon No. 1 Jimmy Bell well (Webster County), where the Eau Claire Formation is absent (Fig. 4.27) and likely faulted out. Where the Eau Claire is absent the overlying carbonates of the Knox would be the primary confining interval. Additional overlying seals would be provided by High Bridge–Trenton carbonates, Upper Ordovician shales (Maquoketa, Clays Ferry, Kope, etc.), and ultimately in some areas the Devonian New Albany Shale (Figs. 4.4–4.5).

CO_2 Storage Potential. Data are insufficient to make a quantitative assessment of the basal sandstone's storage potential in western Kentucky, although data from the two aforementioned wells suggest little potential for large-scale CO_2 storage. More study of the sand's possible origins and potential for secondary porosity development is needed.

Mount Simon Sandstone

CO_2 unit type: potential regional reservoir
KGS stratigraphic code: 375MTSM
Series/system: Cambrian
Thickness: 0–840(?) ft
Distribution: western (north), central (north), and eastern (north) Kentucky
Number of wells with completion: 1
Number of wells that TD: 1
Approximate number of wells drilled through unit: 20

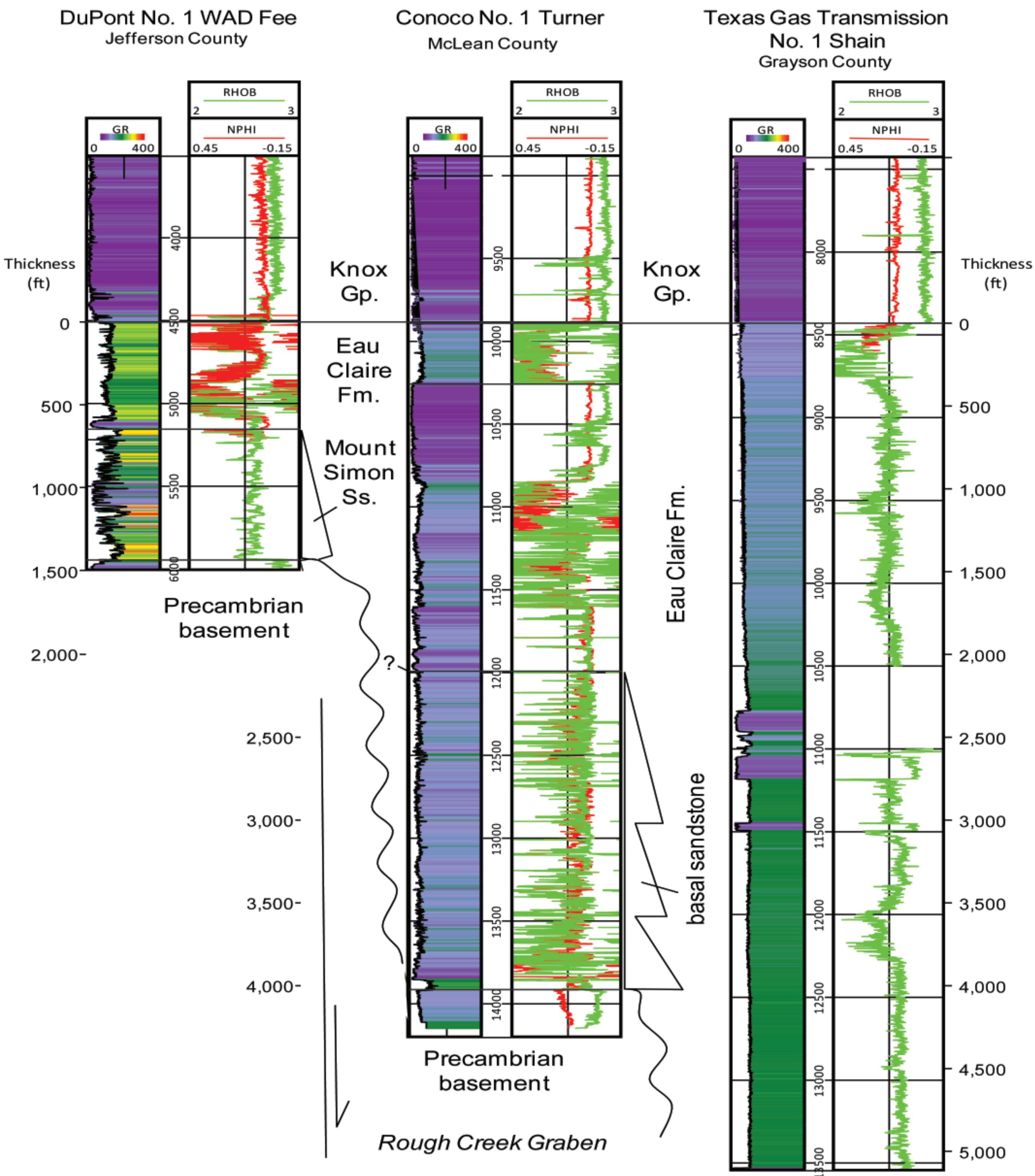

Figure 4.26. Examples of wells that penetrate the Knox Group and deeper in western Kentucky, showing the variable stratigraphy of the Eau Claire Formation, Mount Simon Sandstone, and basal sandstone. Thick basal sandstones have been encountered on the northern margin of the Rough Creek Graben. The wells shown are far apart, and are only depicted to show variability in the lithologies and thickness of units beneath the Knox, rather than representing a true cross section.

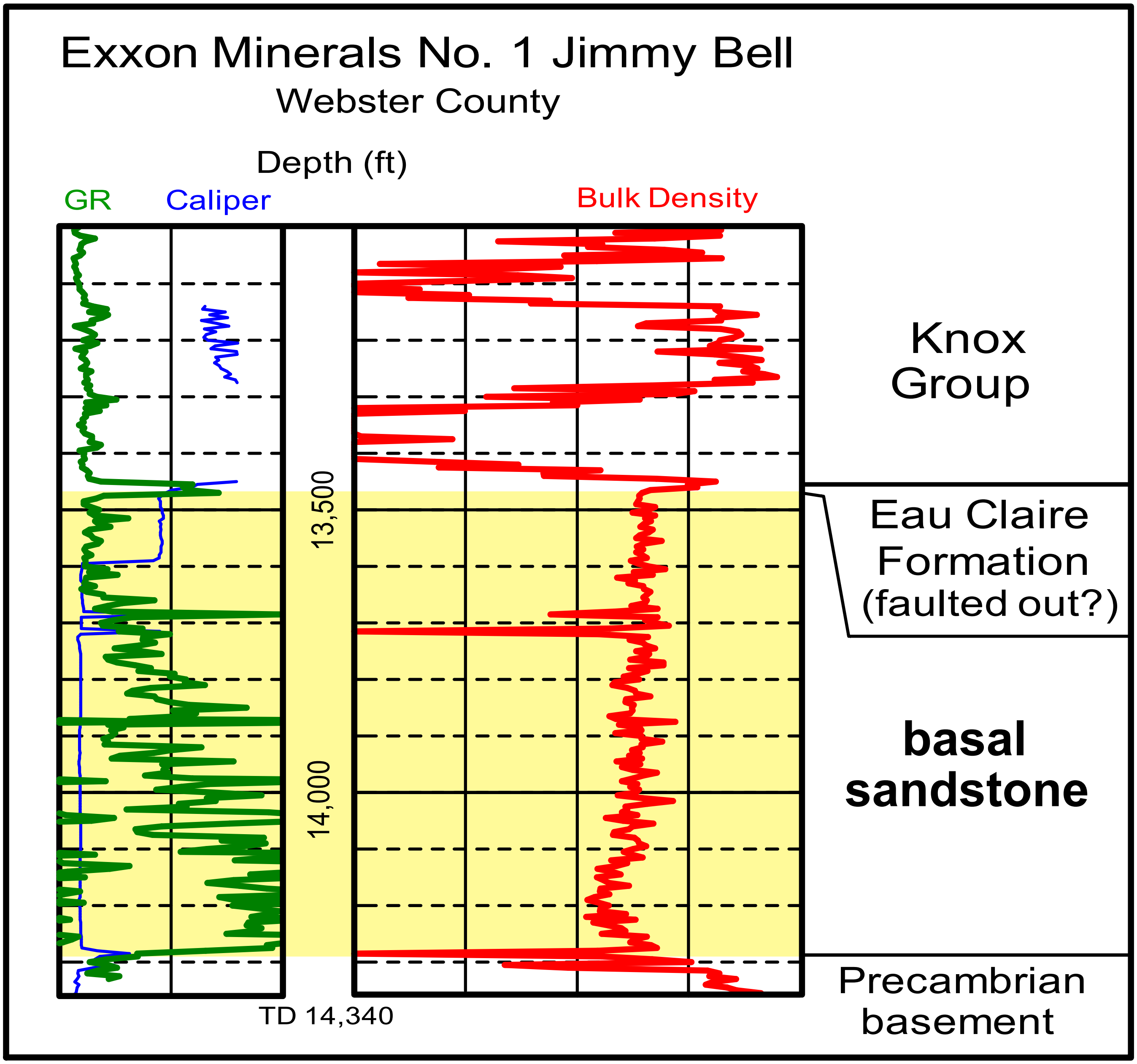

Figure 4.27. Thick basal sandstone in the Exxon No. 1 Jimmy Bell well, Webster County. In this well, the Eau Claire Formation is absent, and was likely removed by faulting. (This well is the westernmost red circle in Figure 4.29.)

Interval Definition. The Mount Simon Sandstone is the first sandstone above the Precambrian unconformity surface in western Kentucky north of the Rough Creek Fault System (Figs. 4.4–4.5), and extends northward into the Illinois and Michigan Basins (Fig. 4.28). On the eastern margin of the Western Kentucky Coal Field, the Mount Simon may extend for a short distance south of the Rough Creek Fault System. In eastern Kentucky, the Mount Simon is only mapped north of the Kentucky River Fault System on the northern margin of the Rome Trough (Fig. 4.9), following the definition of Harris and others (2004). In the Rome Trough, the Mount Simon may be equivalent to the drillers' Kayzee sand of the Maryville Limestone of the Conasauga Group (Figs. 4.4–4.5) (Hickman and Harris, 2004; Harris and others, 2004).

The Mount Simon is overlain by the Eau Claire Formation across most of Kentucky. The contact between the two formations is generally placed at the top of the uppermost sandstone, although the top can

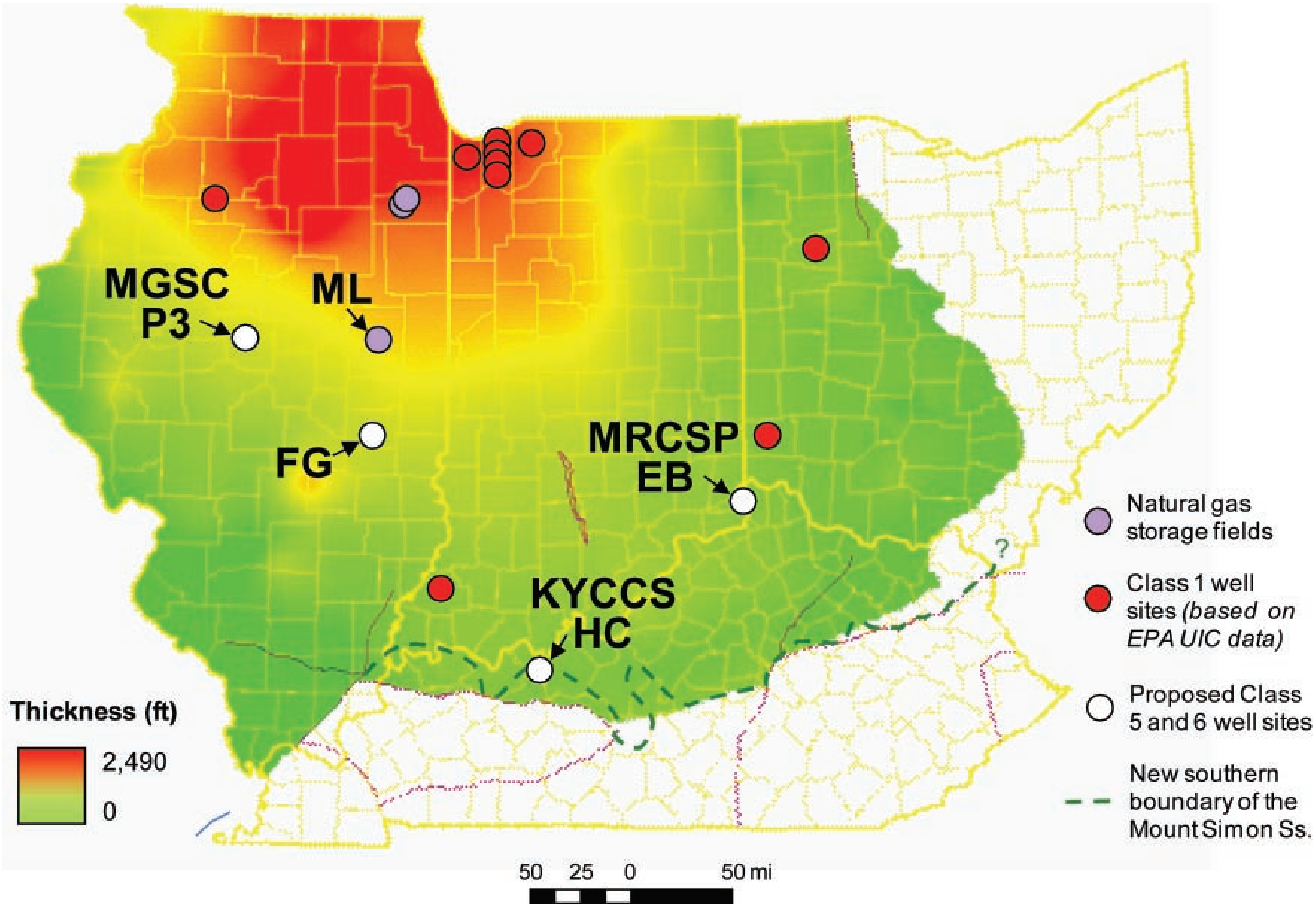

Figure 4.28. Regional thickness of the Mount Simon Sandstone. The Mount Simon Sandstone is a major focus of potential carbon storage in deep, saline reservoirs, which are already used for waste injection (red circles) and underground gas storage (purple circles). Several carbon storage tests are planned in the near future (white circles). FG = Illinois's proposed FutureGen site. KCCS-HC = Kentucky Consortium for Carbon Storage's Hancock County site. MGSC-P3 = Midwest Geological Sequestration Consortium's phase III site. ML = Manlove gas field. Midwest Regional Carbon Sequestration Partnership-EB = Midwest Regional Carbon Sequestration Partnership's East Bend site. Midwest Regional Carbon Sequestration Partnership-P3 = Midwest Regional Carbon Sequestration Partnership's proposed phase III site. The thickness of the Mount Simon Sandstone in Kentucky is updated in subsequent figures.

be gradational. In parts of northeastern Kentucky, the Mount Simon is overlain by the upper Conasauga Group, including the Maryville Limestone and Nolichucky Shale (Figs. 4.44–4.45).

General Description. The Mount Simon Sandstone is a regional saline aquifer and is the target for many carbon storage studies in the Midwest. It is currently used for waste injection and gas (methane) storage in parts of Illinois and Indiana (Fig. 4.28). It was also the primary target for sequestration at the FutureGen project, near Mattoon, Ill., before federal funding for that project was reallocated. Currently, both the Midwest Geological Sequestration Consortium and Midwest Regional Carbon Sequestration Partnership (U.S. Department of Energy–sponsored research groups) have proposed the Mount Simon for their planned phase III (industry-scale) carbon storage projects. The reason the Mount Simon is such a focus for carbon storage in the Midwest is that in parts of Illinois and Indiana, the sandstone is more than 1,000 ft thick and has good porosity. Regionally, however, the sandstone thins to the south and east (Fig. 4.28).

The maximum confirmed thickness of the Mount Simon is 791 ft in the DuPont No. 1 WAD Fee well in Jefferson County (Fig. 4.29), which is close to the maximum projected thickness in Kentucky of 800 ft. Previously, the Mount Simon was interpreted to gradu-

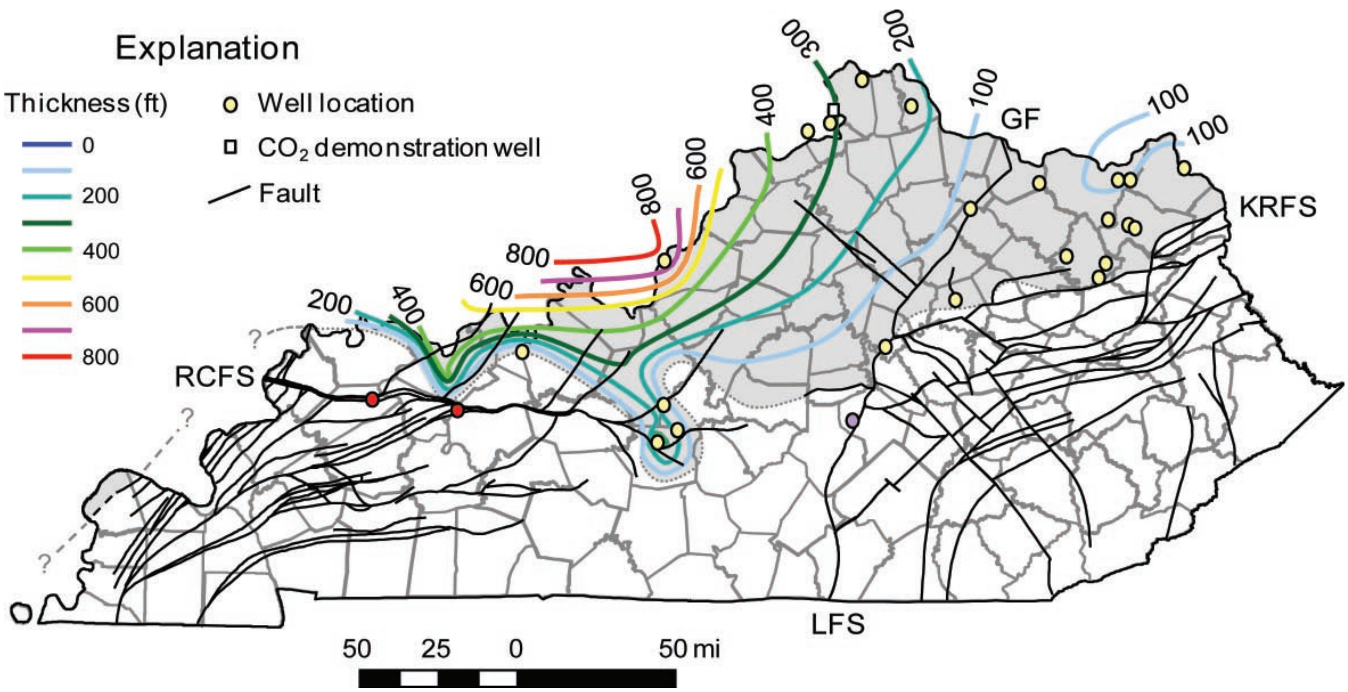

Figure 4.29. Thickness of the Mount Simon Sandstone in Kentucky. The shaded area is the approximate limit of the sandstone based on well data and seismic analysis. The thickness shown is of the entire interval and does not indicate porosity or potential reservoir thickness. Only a small part of this thickness and extent might be available for carbon storage. Three wells (red and purple circles) near the southern limit of the Mount Simon are interpreted to have basal sandstone rather than Mount Simon Sandstone. KRFS = Kentucky River Fault System. LFS = Lexington Fault System. RCFS = Rough Creek Fault System.

ally thicken toward the western margin of the Rough Creek Graben in Kentucky. This trend was based on the assumption that the thick sandstone in the Exxon No. 1 Jimmy Bell well (Fig. 4.27) in Webster County (westernmost red circle in Figure 4.29) was Mount Simon, and was continuous with the Mount Simon known in Jefferson and Hardin Counties. Recently, however, analyses of seismic data have shown that the thick sandstone in the Exxon No. 1 Jimmy Bell and Conoco No. 1 Turner wells (red circles in the western Rough Creek Fault System in Figure 4.29; see also Figures 4.26–4.27) are basal sandstones, rather than Mount Simon Sandstone. The seismic analyses also suggest that the Mount Simon pinches out north of the Rough Creek Fault System in several areas (Jim Drahovzal, 2009, Kentucky Geological Survey, personal communication). This means less Mount Simon in western Kentucky than previously thought.

The Mount Simon Sandstone is deepest (14,000 ft below sea level) in western Kentucky at the far western edge of the Rough Creek Fault System, and becomes shallower to the east where it approaches 2,500 ft beneath the surface (2,000 ft below sea level) in central Kentucky along the Lexington Fault System, above the Grenville Front (Fig. 4.30). It deepens again to the east into the Appalachian Basin, but thins. The sandstone was reported to be 70 ft thick in a well in Scioto County, Ohio, across the river from Greenup County, Ky. Eastward the sandstone also may become arkosic, which influences downhole geophysical log signatures.

Known Reservoirs or Types of Porosity. Few wells penetrate the Mount Simon in Kentucky (Table 4.2), and no wells have had production. The Kentucky Operating No. 1 Riordan well in Hart County—posted as a completion in the Kentucky Geological Survey's Oil and Gas Database—documented "nonmeasurable gas" from the Mount Simon at depths of 7,509 to 7,530 ft (Fig. 4.31). Although not completed as producers, two wells drilled near the Riordan well did find porosity in the Mount Simon (Fig. 4.31).

Regional studies suggest that porosity in the Mount Simon is depth dependent (Hoholick, 1984), with values below 8 percent at 5,000 ft and less than 5 percent below 8,000 ft (Fig. 4.32). The porosity loss with depth relationship is one of the reasons the Kentucky Consortium for Carbon Storage's western Ken-

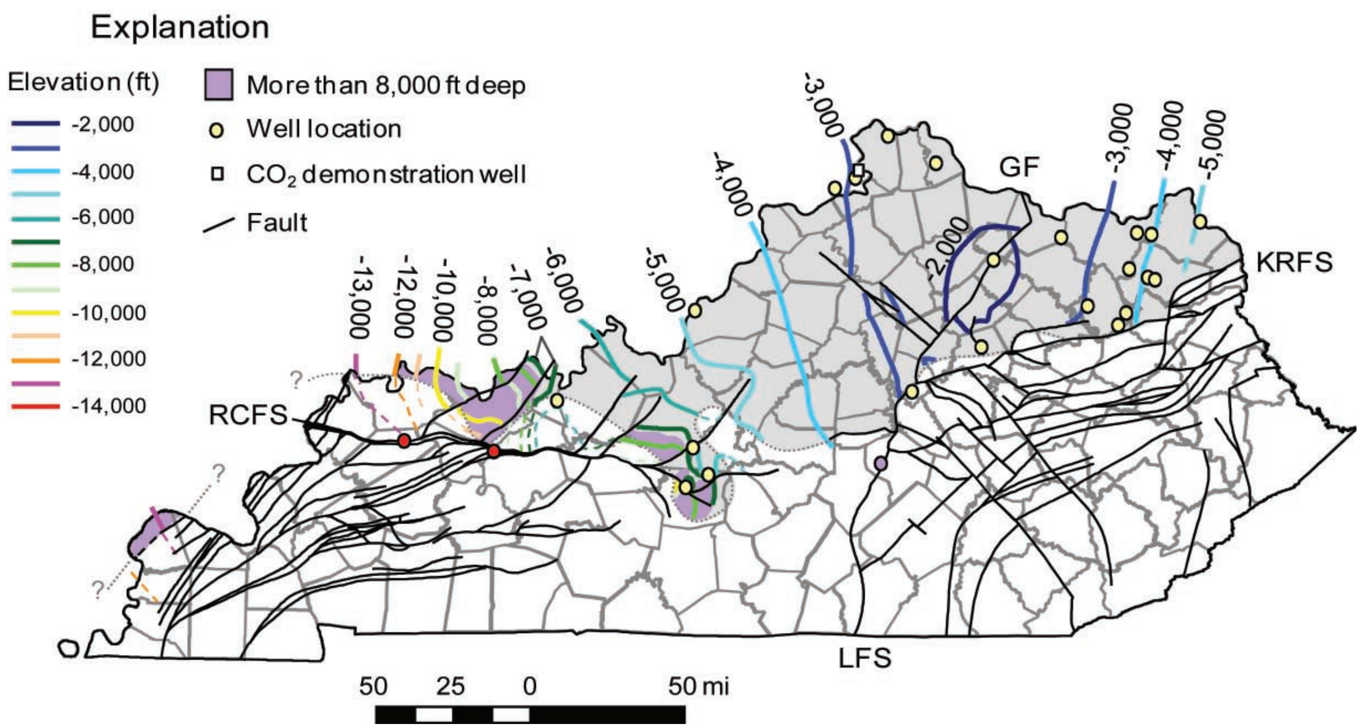

Figure 4.30. Structural elevation on top of the Mount Simon Sandstone. The gray area is the approximate limit of the sandstone based on well data and seismic analysis by Jim Drahovzal (Kentucky Geological Survey). Areas shaded in purple are more than 8,000 ft in depth. Three wells (red and purple circles) near the southern limit of the Mount Simon are currently interpreted to have basal sandstones rather than Mount Simon Sandstone. GF = Grenville Front. KRFS = Kentucky River Fault System. LFS = Lexington Fault System. RCFS = Rough Creek Fault System. Datum is sea level.

tucky carbon storage demonstration well (discussed below) is planned for Hancock County rather than farther west in the coal field, where the sandstone might be thicker, but at greater depths.

Although the Mount Simon Sandstone has a statistically better chance of having better porosity and permeability where it is less than 5,000 ft deep, shallow depths do not guarantee a successful reservoir. For example, the DuPont No. 1 WAD Fee well in Jefferson County drilled into the Mount Simon at 5,200 ft and it did not have sufficient porosity and permeability for the zone to be used for the intended purpose of liquid waste disposal (Fig. 4.33). Instead, DuPont used porous zones in the shallower Knox carbonates (testing data for this well are available in the Kentucky Geological Survey's online Oil and Gas Database at kgsweb.uky.edu/DataSearching/OilGas/OGSearch.asp).

In addition to the variation in porosity for a given depth (Fig. 4.32), reservoir heterogeneity in the Mount Simon of Kentucky is also likely to vary significantly. An examination of the 20 wells that penetrate the Mount Simon in western Kentucky shows that even though the interval may be hundreds of feet thick, sandstone with more than 8 percent porosity is generally less than 30 ft thick. Moreover, sandstone beds are interbedded with shales and siltstones, such as in the Kentucky Operating No. 1 Riordan and K II Inc. No. 1 Brooks wells in Hart County; and the Kentucky Operating No. 1 Sherrard well in Larue County (Fig. 4.31). These wells occur on the eastern margin of the Western Kentucky Coal Field where the Mount Simon Sandstone crosses south of the Rough Creek Fault System. The top of the Mount Simon in these wells is at 6,400 to 7,500 ft and has porosities (based on density logs) of as much as 15 percent. Porous zones are in discrete sandstones separated by nonporous shales and siltstones (Fig. 4.32). Lateral heterogeneity is likely, as in the Cambrian Rome sandstones in eastern Kentucky, Mount Simon Sandstone thickness and porosity may vary across short distances on fault blocks (Fig. 4.31).

CO_2 Injection Demonstrations. The Kentucky Geological Survey No. 1 Marvin Blan well, Hancock County, Ky. (Fig. 4.28), was originally planned to test carbon sequestration in the Mount Simon Sandstone and Knox Group. The well was drilled in the summer

Table 4.2. Wells drilled into or through the Mount Simon Sandstone in Kentucky.

Permit No.	*Well Name*	*County*	*Surface Elevation (ft)*	*Mount Simon Top (ft)*	*Thickness (ft)*
none	Ford F M 1 Conner Cecil	Boone	908	3,427	268
18051	Ashland Oil & Ref. 1 Wilson Harold	Campbell	747	3,155	236
398E9	United Fuel Gas Co. 8807T Stamper	Carter	846	5,006	42
16235	Ashland Oil & Cabot 11-1 Stapleton	Carter	948	5,192	26
18142	Ashland Oil & Ref. 1 Miller	Clark	940	3,050	26
271E0	United Fuel Gas Co. 8802T Litton	Elliott	968	5,173	17
14723	Ford R C Jr. 1 Delaney	Grant	867	3,390	167+
21256	Commonwealth Gas Corp. 1 Newell	Greenup	1,043	5,062	116
87916	Ky. Operating Inc. 1 Riordan	Hart	684	7,495	35
89059	K II Inc. 1 Brooks	Hart	723	6,401	59
24576	E I DuPont de Nemours 1 WAD	Jefferson	452	5,192	752
88556	Kentucky Operating LLC 1 Sherrard	Larue	721	6,600	195
2579	United Fuel Gas Co. 9060 Shephard	Lewis	903	4,499	30
	Thomas Ralph N 1 Adams	Lewis	555	4,112	35
21132	Ashland Oil & Refining 1 Wolfe	Lewis	1,102	5,007	16
3990	United Fuel Gas Co. 9061T Rawlings	Mason	764	3,274	16
30197	Union Light Heat & Power 200 Mynear	Nicholas	695	2,843	80
25356	Kentucky Central & Co. 1 Perkins	Rowan	1,231	4,947	21
14647	Pennzoil Co. 1 Jones	Rowan	1,194	4,942	25
22478	Peter Henderson Oil Co. 1 Bailey	Rowan	727	3,754	26
29845	Exxon Minerals Co. USA 1 Bell	Webster	395	13,470	810

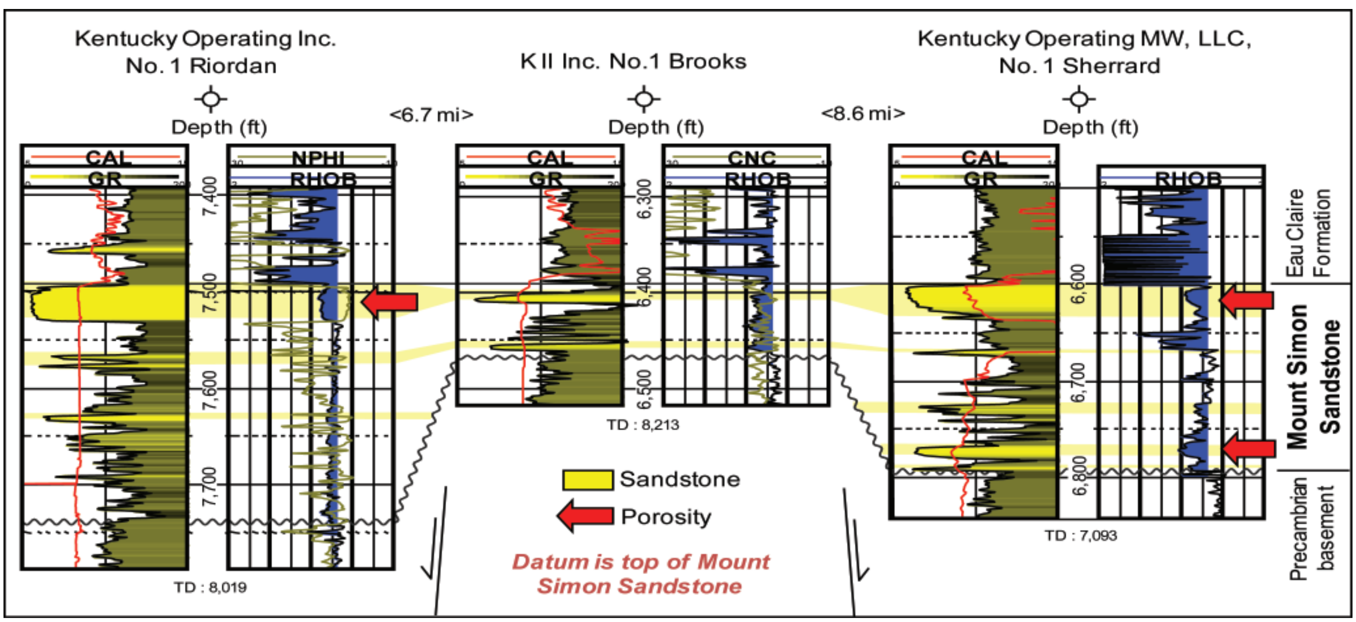

Figure 4.31. Three wells on the eastern end of the Rough Creek Graben have drilled into the Mount Simon Sandstone. In this area the unit varies in thickness across fault blocks, and consists of interbedded sandstones (yellow) and shales.

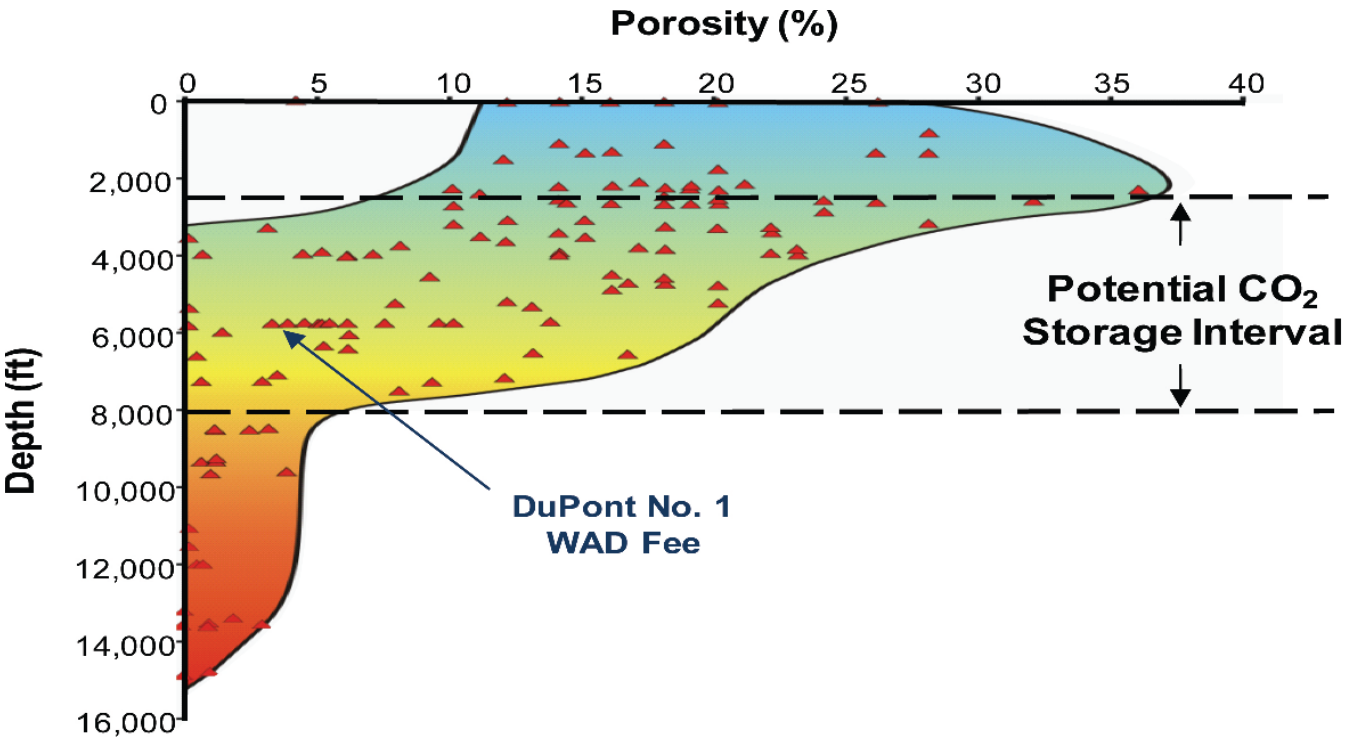

Figure 4.32. Porosity versus depth relationship for the Mount Simon Sandstone in the Illinois Basin. Based on 828 samples from Rick Bowersox, Kentucky Geological Survey (based on data from Metarko [1980], 89 samples; Shebl [1985], nine samples; Makowitz [2004], 27 samples; Kunledare [2005], 690 samples; and the DuPont No. 1 WAD Fee well, 13 samples).

of 2009 to a depth of more than 8,000 ft in Precambrian basement. Prior to drilling, analysis of seismic data indicated the Mount Simon would be very thin or absent (below the thickness detectable by seismic data). The sandstone proved absent in the well, which shows the importance of seismic analysis prior to drilling. More information on this well can be found at the Kentucky Consortium for Carbon Storage Web site (www.uky.edu/KGS/Kentucky Consortium for Carbon Storage/).

The Midwest Regional Carbon Sequestration Partnership drilled a CO_2 injection demonstration well at Duke Energy's East Bend power station in Boone County, Ky. (Fig. 4.28) as part of phase II research under the U.S. Department of Energy's Regional Carbon Sequestration Partnerships program. The well was drilled in the summer of 2009 and injection testing was completed in September. In the well, the Mount Simon Sandstone is 300 ft thick, at depths of 3,253 to 3,553 ft. Geophysical logging and coring indicated good porosity in the lower part of the unit. Preliminary results indicate 1,000 short tons of CO_2 were injected into the Mount Simon at four barrels per minute, which was the limit of the pumps. This was the first injection of CO_2 into the Mount Simon Sandstone. Reports from this demonstration are pending, but preliminary information, including fact sheets for this project, can be found at the Midwest Regional Carbon Sequestration Partnership Web site (216.109.210.162/).

In future research under the same sequestration program (phase III), the Midwest Regional Carbon Sequestration Partnership had planned a test of the Mount Simon at the Anderson Marathon ethanol plant near Greenville, Ohio. Those plans, however, fell through when there was opposition from the public around the plant. A new phase III site has not been chosen.

In the Illinois Basin, the Midwest Geological Sequestration Consortium (managed by the Illinois State Geological Survey), as part of their sequestration partnership phase III work, is planning a test of the Mount Simon at the Archer Daniel Midland's Decatur plant near Decatur, Ill. The Mount Simon is anticipated to be at a depth of approximately 500 ft and more than 1,500 ft thick at that location. Approximately 1 million short tons of carbon dioxide generated from the ethanol plant will be injected into the Mount Simon during a 3-year period. Planning for this project began in 2008,

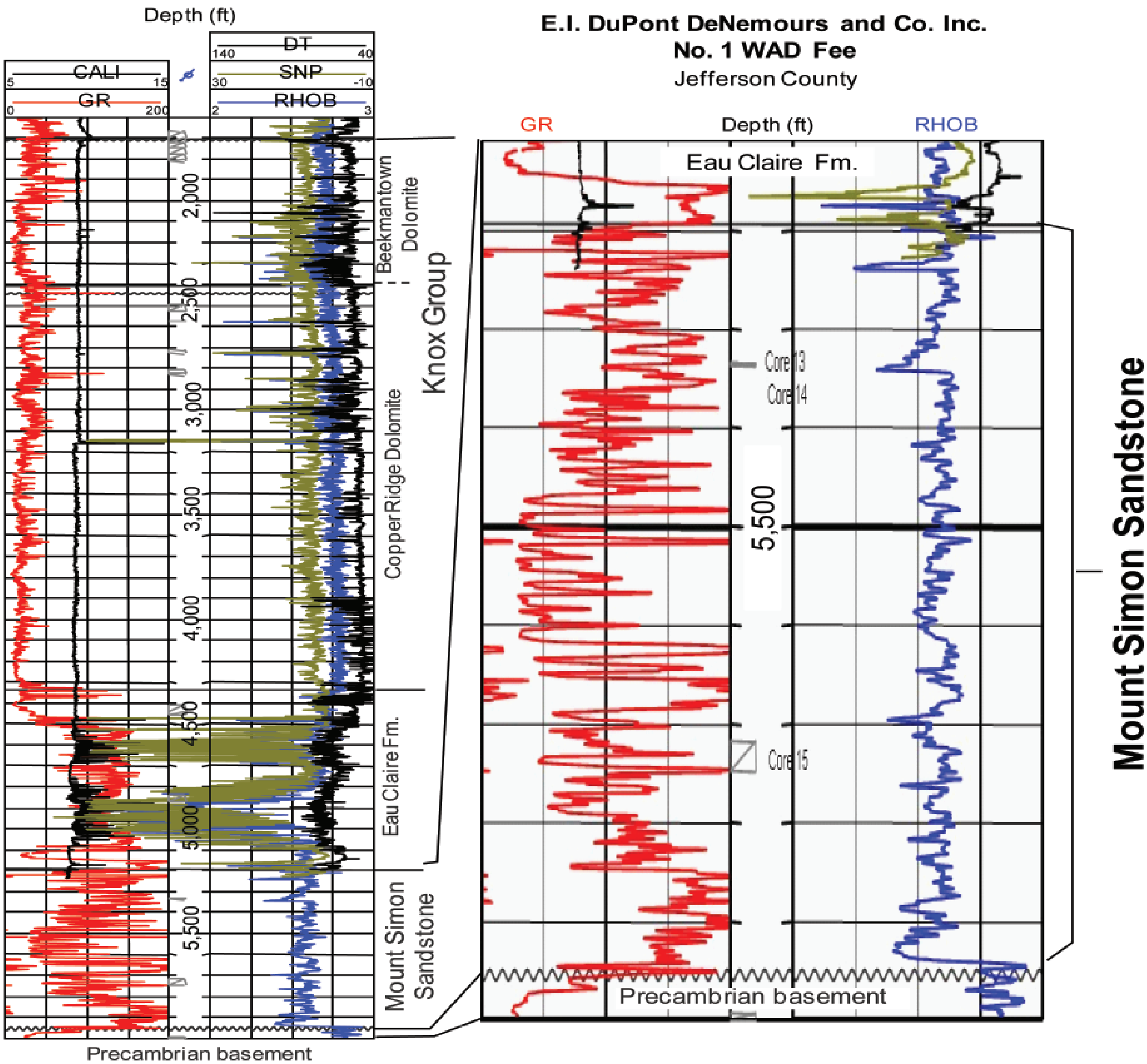

Figure 4.33. Mount Simon Sandstone in the DuPont No. 1 WAD Fee well, Louisville, Ky.

and the first injection is planned for 2009. More information, including fact sheets for this project, can be found at the Midwest Geological Sequestration Consortium Web site (sequestration.org/).

Overlying Sealing/Confining Units. The Eau Claire Formation, where it is unfaulted, is the primary confining interval for the Mount Simon reservoir. Few wells penetrate the Eau Claire, so leakage up old wellbores should not be an issue. Thick, overlying Knox and Middle and Upper Ordovician (Black River–Trenton) carbonates would form secondary seals (Figs. 4.4–4.5). The ultimate seal would be the Upper Ordovician shale interval. The stratigraphically higher Devonian shale would also be a confining interval, off of the Cincinnati Arch.

CO_2 Storage Potential. As evidenced by the planned carbon storage tests, interest in the Mount Simon as a regional storage aquifer has been significant. Nowhere in Kentucky is the Mount Simon less than 2,500 ft deep, so it is below the level needed for supercritical CO_2 injection. Also, the Mount Simon has no gas production, so leakage up old wellbores or interference with existing energy resources should not be an issue. The Mount Simon of eastern Kentucky was calculated to have potential volumetric storage capacity of more than 47.8 billion short tons (43.36 billion metric tons) in the phase I report of the Midwest Regional Carbon Sequestration Partnership (Wickstrom and others, 2005). If only 10 percent of that volume has storage potential, 4.7 billion short tons (4.3 billion metric tons) of storage would be available; if 1 percent, then 0.5 billion short ton (0.4 metric ton) would be available.

The Midwest Geological Sequestration Consortium estimated Mount Simon storage capacity in western Kentucky at 6.3 billion short tons (5.7 billion metric tons) and 1.5 billion short tons (1.4 billion metric tons) for 4 percent and 1 percent of total volume, respectively (Frailey and others, 2005). The actual capacity, however, may be somewhat lower for two reasons. First, the sandstone is more than 8,000 ft deep in several areas, so porosity may not be good enough for injecting large volumes of CO_2, based on inferred depth-porosity relationships. Second, recent seismic analysis suggests that the Mount Simon Sandstone north of the Rough Creek Fault System is not as broadly distributed as it was thought to be when the original capacity estimates were made. That said, the Mount Simon is at adequate depths for storage in much of the northern quarter of Kentucky, and further assessments of the unit's storage potential will be provided through planned demonstration tests in the region.

Eau Claire Formation

CO_2 unit type: primary confining unit (seal)
KGS stratigraphic code: 375ECLR
Series/system: Cambrian
Thickness: 350–2,760 ft (in Rough Creek Graben, thickness of Eau Claire and deeper strata may exceed 10,000 ft[1])
Distribution: western and central Kentucky
Number of wells with completion: 0
Number of wells that TD (or penetrate): 5
Approximate number of wells drilled through unit: 16

Interval Definition. The Eau Claire Formation includes all strata from the top of the Mount Simon Sandstone, basal sandstone, or the top of the Precambrian where the sandstones are missing to the base of the Copper Ridge (lower Knox) Dolomite in western and central Kentucky (Figs. 4.4–4.5). The upper contact is sharp. In eastern Kentucky, the Eau Claire is equivalent to the upper Maryville Limestone, Nolichucky Shale, and Maynardville Limestone (Harris and others, 2004). The boundary between the Eau Claire and Conasauga is arbitrarily placed near the Grenville Front in the area where the Conasauga thins and the Maynardsville Limestone pinches out, but well control is insufficient to document the boundary; therefore, it is shown as a sawtoothed color break in Figure 4.20. Interbedded limestone and shale that may be equivalent to the Maynardsville Limestone in eastern Kentucky may extend west to Boone County, Ky. In southeastern Indiana, a stratigraphically equivalent limestone is called the Davis Formation in Indiana. This interval of interbedded limestone and shale would generally be combined with the Eau Claire Formation in western Kentucky. In south-central Kentucky, the boundary between the two units is herein placed at the Lexington Fault System on the western edge of the Rome Trough.

General Description. The Eau Claire is not exposed at the surface in Kentucky. It is shallowest — less than 1,500 ft below sea level — along the Lexington Fault System above the Grenville Front in east-central Kentucky (Fig. 4.34). It deepens to more than 14,000 ft below sea level in the western part of the Rough Creek Graben. The Eau Claire is described in Avila (1981) and Shaver and others (1986). Sample descriptions are included in well reports from the Conoco No. 1 Turner well (McLean County), the Exxon No. 1 Duncan well, (Webster County — called Conasauga in formation record), and Texas Gas Transmission No. 1 Shain well (Grayson County). The well records can be accessed online at the Kentucky Geological Survey's Oil and Gas Database. The reports and well records indicate that the Eau Claire Formation is composed of brown, gray, green, and maroon shales, which can be micaceous; feldspathic, micaceous, and partly glauconitic siltstone; very fine-grained to fine-grained, well-sorted sandstone (feldspathic and lithic); and fine-grained to coarsely crystalline, sandy to silty, glauconitic dolomites and limestones. Analysis of subsurface well logs shows that the Eau Claire thickness ranges from 361 to 565 ft. It is thinnest on the Cincinnati Arch in central Kentucky, and thickens into the Rough Creek Graben.

In eastern Kentucky the Conasauga Group (equivalent to the Eau Claire Formation) is underlain by thousands of feet of the older Rome Formation, which is confined to the Rome Trough. There may be a similar situation in western Kentucky for the Eau Claire Formation. North of the Rough Creek Graben, the Eau

[1]Includes strata confined to the graben.

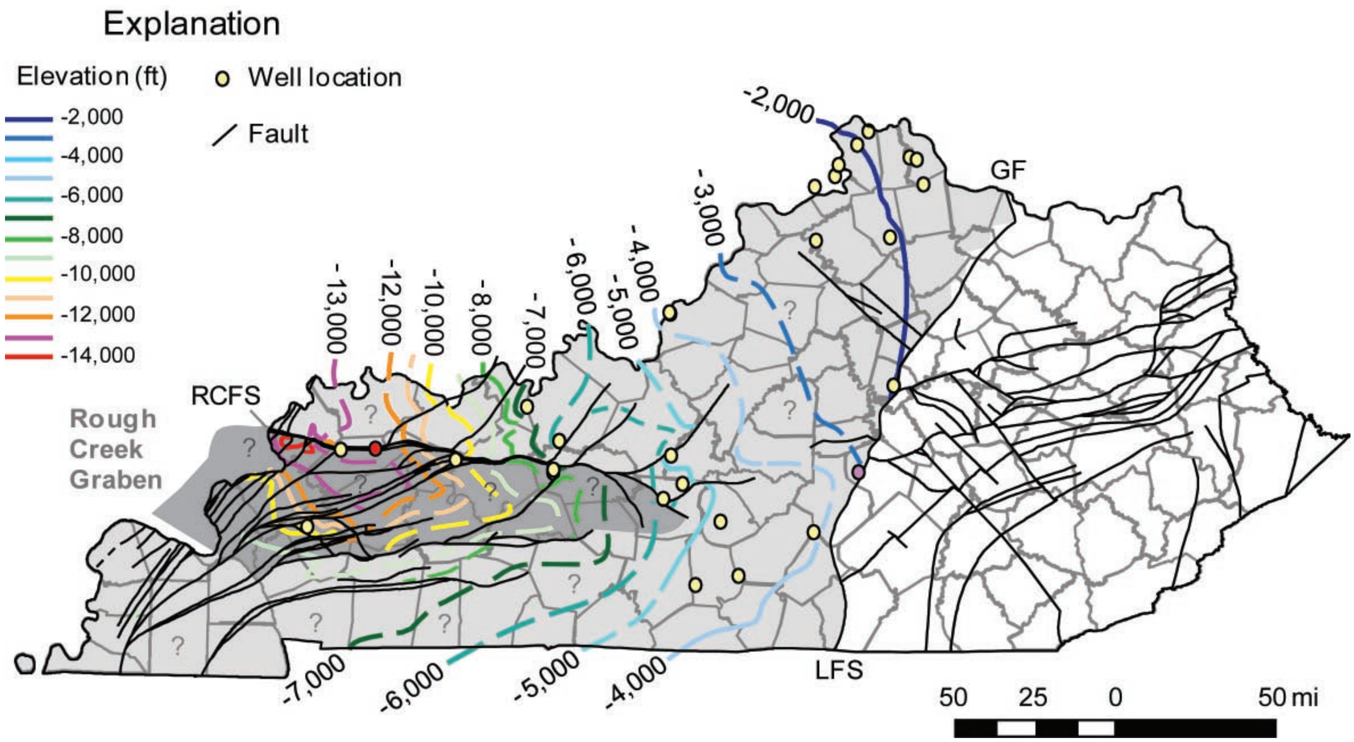

Figure 4.34. Structure on top of the Eau Claire Formation (gray background). The thickest Eau Claire strata is in the Rough Creek Graben (dark gray background). Structure on top of the equivalent Conasauga Group of eastern Kentucky is shown in Figure 4.22. Contour interval is 1,000 ft out of the Rough Creek Graben and 2,000 ft within the graben. GF = Grenville Front. LFS = Lexington Fault System. RCFS = Rough Creek Fault System. The well location shown in red is the Exxon No. 1 Jimmy Bell well in which the Eau Claire is missing and likely removed by faulting (see Figure 4.27). The well shown in purple contains strata that may indicate a slight western extension of the Rome Trough. Interpretations in western Kentucky are partly based on preliminary seismic data from Jim Drahovzal (Kentucky Geological Survey) and from Noger and Drahovzal (2005).

Claire is hundreds of feet thick. On the northern margin of the graben, the Texas Gas Transmission No. 1 Shain well (Grayson County) encountered more than 5,000 ft of strata beneath the Knox Group (Figs. 4.26, 4.35). Originally, only 2,760 ft of the strata beneath the Copper Ridge Dolomite was identified as Eau Claire Formation, which is similar to the 2,008(?) ft of Eau Claire encountered in the Conoco No. 1 Turner well (Fig. 4.26). An additional 2,500 ft of strata (mostly shale), however, occurs below a “granite wash” in the well. In western Kentucky, a deeper unit (analogous to the Rome Formation in eastern Kentucky) has not been defined. Hence, all strata between the basal sand or basement and the base of the Knox are combined into the Eau Claire Formation for the purpose of this report.

Whether or not the complete thickness of shaly strata is Eau Claire or Eau Claire plus units that have not been defined to date, very thick shales, siltstones, and limestones are in the Rough Creek Graben beneath the Knox Group. In the western, deeper parts of the graben, no well has penetrated the complete thickness of this interval, and the Eau Claire (plus underlying units to Precambrian basement) could be more than 15,000 ft thick, based on seismic interpretations (Noger and Drahovzal, 2005). The Kentucky Geological Survey is currently analyzing seismic data across the graben as part of the Rough Creek Graben Consortium. These analyses should provide better interpretations of the depths and structure of the deep strata in the graben. Information on this project will be available at the Kentucky Geological Survey Web site (www.uky.edu/KGS/).

Known Reservoirs or Types of Porosity. The Eau Claire is not productive and has only locally developed porosity; therefore, it is considered a confining interval for deeper Mount Simon and basal sandstones, especially north of the Rough Creek Fault System.

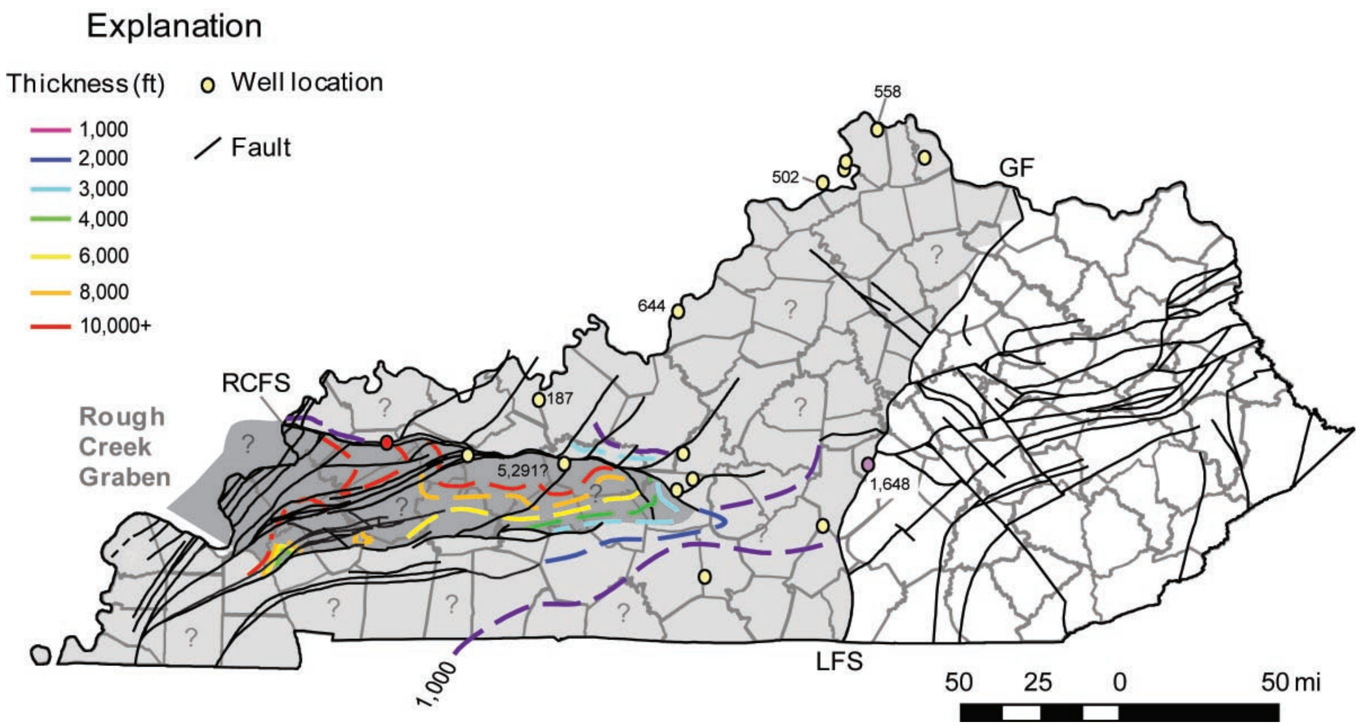

Figure 4.35. Thickness of the Eau Claire Formation in western Kentucky (shaded gray) and partly equivalent Conasauga Formation (white) in eastern Kentucky. GF = Grenville Front. LFS = Lexington Fault System. RCFS = Rough Creek Fault System. The well location shown in red is the Exxon No. 1 Jimmy Bell well in which the Eau Claire is missing and likely removed by faulting (see Figure 4.27). The well shown in purple contains strata that may indicate a slight western extension of the Rome Trough. Elevations in western Kentucky are partly based on preliminary seismic interpretations from Jim Drahovzal (Kentucky Geological Survey) and from Noger and Drahovzal (2005). Thicknesses in the Rough Creek Graben include strata that are older than the Eau Claire Formation north of the Rough Creek Fault System.

Overlying Sealing/Confining Units. The Eau Claire, where it is unfaulted, would be the primary seal for storage in the Mount Simon or Middle Run Formations. Few wells penetrate the Eau Claire, so leakage up old wellbores should not be a major issue where underlying strata are used as storage reservoirs. Stratigraphically higher sealing intervals are the Middle Ordovician (Trenton–Black River) carbonates, and in the basins off the Cincinnati Arch, the Upper Ordovician and Devonian shales. Samples of the Eau Claire are being collected as part of regional carbon storage research to test the unit's mineralogy and mechanical properties to better characterize its confining capabilities.

CO_2 Storage Potential. Overall, limestones and shales of the Eau Claire Formation lack significant porosity and are therefore considered seals or confining intervals with little or no carbon storage potential.

Lower Knox Carbonates

CO_2 unit type: possible regional/local reservoirs and secondary confining unit
KGS stratigraphic code: 372KNOXL, 372CPRG
Series/system: Cambrian
Thickness: 600–4,800 ft
Distribution: statewide
Number of wells with completion: 2
Number of wells that TD: 93[1]
Approximate number of wells drilled through unit: 110

Interval Definition. The Copper Ridge Dolomite comprises the lower Knox in most of Kentucky. The

[1]This is the number of wells that specifically designate their TD as lower Knox or Copper Ridge. More than 11,000 wells (mostly on the Cincinnati Arch at shallow depths) penetrate part of the Knox (general) and list the Knox as TD. Some of these may include the Copper Ridge, although most are limited to the Beekmantown or upper Knox.

Copper Ridge extends from the top of the Eau Claire Formation and Conasauga Groups to the base of the Rose Run Sandstone in eastern and central Kentucky or Gunter Sandstone in western Kentucky. Where the sandstones are absent, the Beekmantown or Gasconade Dolomite form the upper contact with the Copper Ridge; discriminating this contact can be difficult (Figs. 4.4–4.5). Differentiating sandy zones equivalent to the overlying Rose Run or Gunter Sandstones requires a log suite that can detect sandy carbonates or detailed sample descriptions to detect sand grains in carbonates. In far western Kentucky, the Copper Ridge is equivalent to the Eminence, Potosi, and Elvins Formations.

General Description. The Copper Ridge is a thick, tan to brown, crystalline dolomite with interbeds of sandstone and dark gray, argillaceous limestone (McGuire and Howell, 1963; Shrake and others, 1990; Ryder and others, 1996, 1997). This dolomite is extensive across the eastern and midcontinent United States. The origin of such a widespread dolomitic unit continues to be enigmatic, although it may be related to alteration of carbonates by mineralizing fluids that were expelled from Ordovician Sevier (Glumac and Walker, 2000) or later Paleozoic Alleghanian (Montanez, 1994) mountain-building episodes on the eastern margin of the North American continent.

In western Kentucky, Copper Ridge sample descriptions were included in reports from the Conoco No. 1 Turner (McLean County), Exxon No. 1 Duncan (Webster County), and Texas Gas Transmission No. 1 Shain (Grayson County) wells. Data from these wells can be accessed online at the Kentucky Geological Survey's Oil and Gas Database. For eastern Kentucky, sample descriptions from 11 wells are provided in McGuire and Howell (1963).

The lower Knox interval is thickest in the Rough Creek Graben of western Kentucky, although its actual thickness is difficult to assess where the Gunter Sandstone is thin or missing and the lower and upper Knox cannot be discriminated. Seismic resolution of the lower and upper Knox is also difficult because there is little difference in density between the two units and therefore minimal acoustic impedance contrast. Where the Copper Ridge Dolomite (and equivalents) has been identified in western Kentucky wells, it generally comprises more than half to two-thirds of the total Knox thickness.

The total Knox thickens toward the north side of the graben, and from east to west in the graben, based on available data. The thickest confirmed total Knox is 5,997 ft in the Sun Oil Co. No. 1 Stearns well in Caldwell County, but the Knox interval may be 7,000 ft or more thick in the Eagle Valley Syncline of McLean County, on the north side of the graben (Noger and Drahovzal, 2005). The Knox interval is less than 2,000 ft thick north of the Rough Creek Fault System and south of the graben (Fig. 4.36). The total Knox thickens toward the north side of the graben, and also from east to west in the graben. The Copper Ridge (lower Knox) presumably follows the same trend as the total Knox. The thickest Copper Ridge in a well is likely in the Exxon Jimmy Bell well in Webster County, although some of the Knox may be overthickened because of faulting.

The Copper Ridge is generally easier to map in eastern than western Kentucky, because the overlying Rose Run Sandstone is more persistent and more wells have been drilled through the interval there. The Copper Ridge is thinnest in eastern Kentucky above the Waverly Arch (Woodward, 1961), and is less than 1,000 ft thick in many areas. The Copper Ridge also thins above the Grenville Front–Lexington Fault System (Fig. 4.36). Unlike in western Kentucky, the thickness of the Copper Ridge is not strongly symmetrical with the Rome Trough (Fig. 4.36). There is some thickening into the trough, especially on the west end, but not to the degree seen in the Rough Creek Graben, nor to the degree seen in preceding intervals. The Copper Ridge is shallowest in central Kentucky, where the top is at less than 1,000 ft below sea level. The interval is less than 2,500 ft deep across much of north-central Kentucky. In eastern Kentucky, the lower Knox deepens gradually to the east, to more than 9,800 ft (9,000 ft below sea level) in easternmost Pike County (Fig. 4.37). In contrast, the top of the Copper Ridge is estimated to be nearly 11,000 ft deep in the Webster County Syncline, just south of the Rough Creek Fault System (Fig. 4.37). Offsets of the Copper Ridge along faults in the Rome Trough are generally less than 600 ft, whereas in the Rough Creek Graben, offsets can be as much as 2,000 ft.

Known Reservoirs or Types of Porosity. Evidence of porous zones capable of conducting fluids in the Copper Ridge is provided through a limited number of wells that produce hydrocarbons and by wells used for waste disposal. Two producing wells in Johnson County — the Ashland Oil Exploration No. 1 Bayes and No. 1 Tackett — produced gas from depths of

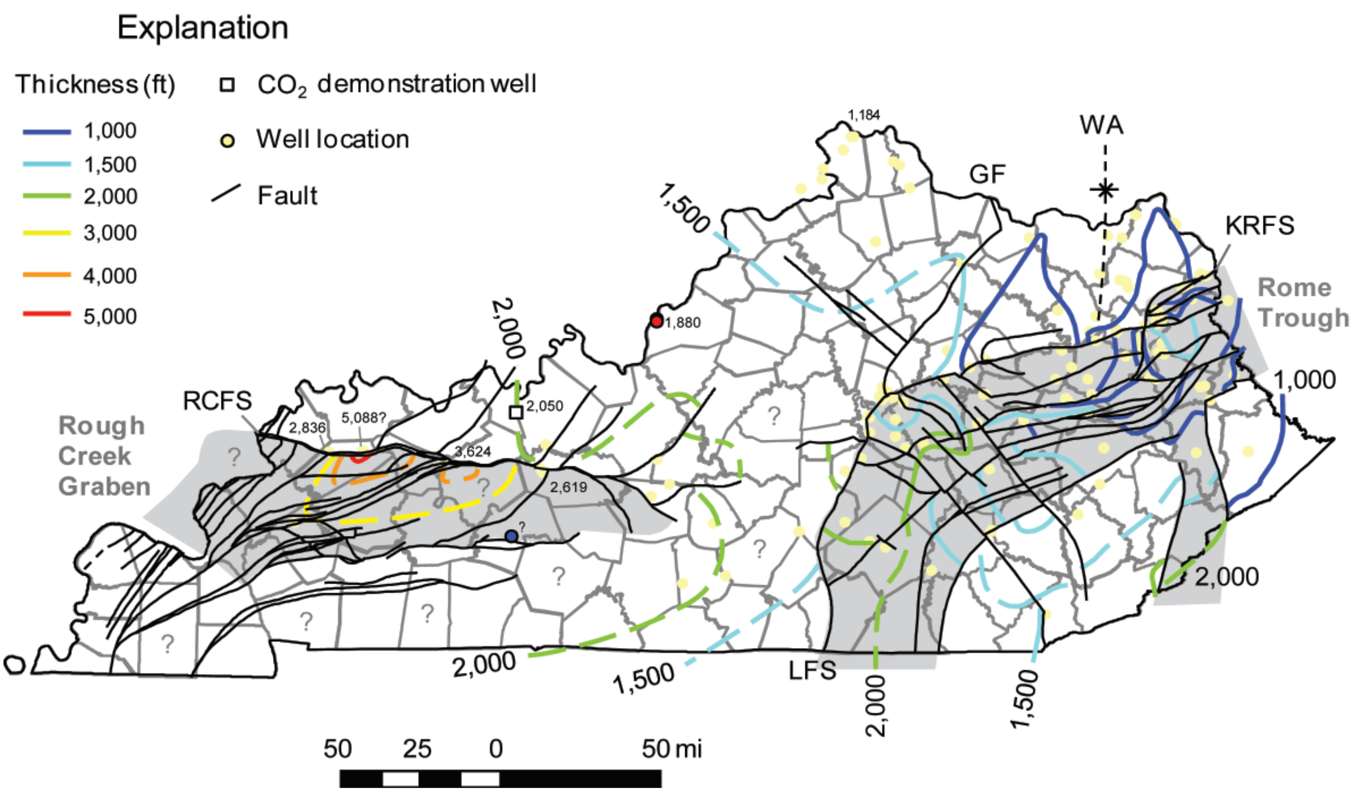

Figure 4.36. Thickness of the lower Knox interval (Copper Ridge Formation). Contour interval is 500 ft outside of the Rough Creek Graben and 1,000 ft within the graben. The thickness shown here does not indicate porosity or potential reservoir thickness. Only a small part of this thickness and extent might be available for carbon storage. Structural grabens are shaded gray. Red circles are the locations of the DuPont injection wells in Jefferson County. The blue circle is the IMCO Recycling injection well in Butler County, which may include the lower Knox. GF = Grenville Front. LFS = Lexington Fault System. RCFS = Rough Creek Fault System. WA = Waverly Arch.

5,742 ft and 5,553 ft (731 ft and 501 ft from the top of the Copper Ridge), respectively. Both wells are part of the Mine Fork Pool just south of the Irvine–Paint Creek Fault System. In spite of the lack of hydrocarbon production, the Copper Ridge generally contains discrete intervals of vuggy, algal, and fracture porosity. Porosity zones in the Copper Ridge have been used for waste disposal in Kentucky, which are summarized in the following section.

Waste Injection Wells. The lower Knox (Copper Ridge and Potosi Dolomites) has been used for waste injection in Illinois and Kentucky (Avila, 1981; Stevenson, 1982). Waste injection wells at the Cabot Corp. near Tuscaloosa, Ill., had good pump rates and a lack of substantial pressure change, suggesting that there was a large reservoir that could accept injected fluids (Stevenson, 1982). In Kentucky, waste disposal in the Copper Ridge occurred in two Class 1 waste injection projects in Jefferson and Butler Counties.

The E.I. DuPont No. 1 and No. 2 waste acid disposal (WAD) wells in Jefferson County (red circles in Figures 4.36 and 4.37) were drilled in 1971 and 1972 to test the Mount Simon Sandstone as a potential injection reservoir for pickling brine produced at DuPont's plant in Louisville. The No. 1 WAD targeted the Mount Simon at a depth of 5,192 ft, but extensive testing showed that the sandstone did not meet their criteria for injection. Fortunately, geophysical logs and cores showed that the lower Knox contained porosity zones at shallower depths (Fig. 4.38).

Although not taken from the zone ultimately used for injection, cores from the No. 1 and No. 2 WAD wells show various types of porosity, including fractures with rounded margins—presumably from dissolution, vugs partly cemented with calcite and dolomite, and moldic porosity in algal laminations (Fig. 4.39). Permeability ranges from 632 to less than 1 md, but the average of values with horizontal permeability that were similar in both directions was 60.0 md. Large differences in measurements of horizontal permeability

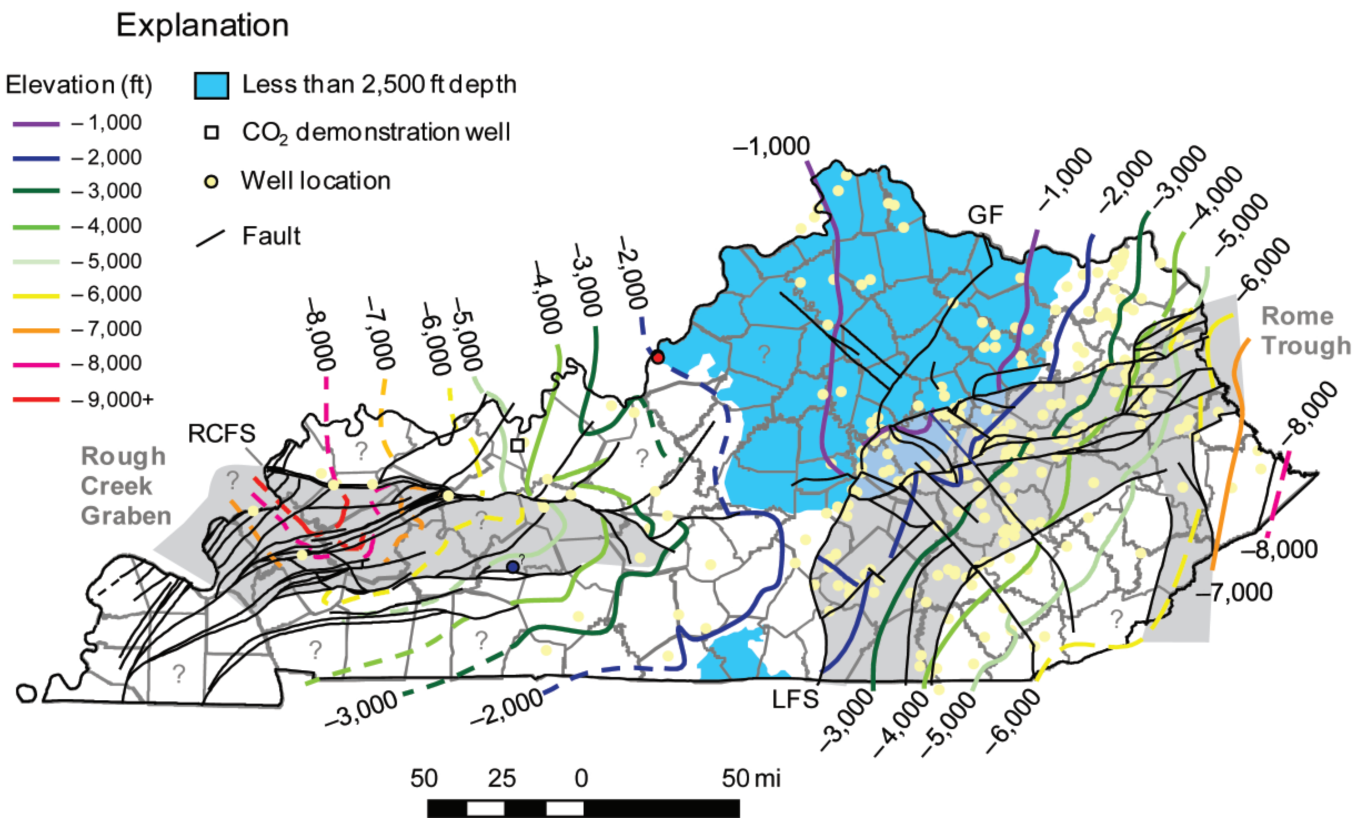

Figure 4.37. Structural elevation on top of the lower Knox interval (Copper Ridge Formation). Area where the lower Knox is approximated to be less than 2,500 ft is shaded in light blue. Structural grabens are shaded gray. Question marks imply uncertainty. Red circles are the locations of the DuPont injection wells in Jefferson County. The blue circle is the IMCO Recycling injection well in Butler County, which may include some of the lower Knox Group.

in two orthogonal directions for several tests suggest a component of fracture-related permeability and likely a dual porosity system with fracture or vuggy porosity. Extensive monitoring at the DuPont site showed that injection occurred in approximately 40-ft-thick, elongate cavities in the wells, one approximately 250 ft long, the other 500 ft long. Cavities were separated and oriented along fractures in the Copper Ridge. The acidic fluids reacted with carbonates in the reservoir and created carbon dioxide. The CO_2 rose to the top of the cavity and remained trapped within the formation. This is the first documented CO_2 that has been sequestered in the state as a result of injection (albeit indirectly). The site received an approved chemical-fate, no-migration demonstration from the Environmental Protection Agency in 1990, which means that the injected fluids in the well (and produced CO_2) were safely held within the Copper Ridge reservoir on site and there was no indication that they had migrated out of the reservoir zone.

The IMCO Recycling Inc. well in Butler County (blue circle in Figures 4.36 and 4.37) has been operating as a nonhazardous Class 1 disposal well for brine and landfill runoff since 1995. The reservoir for waste disposal is the Knox Group (both the upper and possibly lower Knox). This well has yet to be correlated with wells to the north; hence, the top of the Copper Ridge is uncertain although it may be penetrated in the lower part of the well. A description of this well is included in the upper Knox section of this report.

Eastern Kentucky Deep Porosity. McGuire and Howell (1963) reported numerous zones of vugular and intercrystalline porosity from the Knox (some of it in the lower Knox) in eastern Kentucky. Shows of oil or gas from the Knox have been reported from wells in Bell, Breathitt, Carter, Elliott, Leslie, Lewis, Lincoln, Mason, Rowan, Perry, Powell, and Wolfe Counties. Specific examples of wells are the United Fuel Gas No. 1 Fordson Coal in Leslie County, which had gas shows at 7,000 ft, and the Arco No. 1 Duff well in Per-

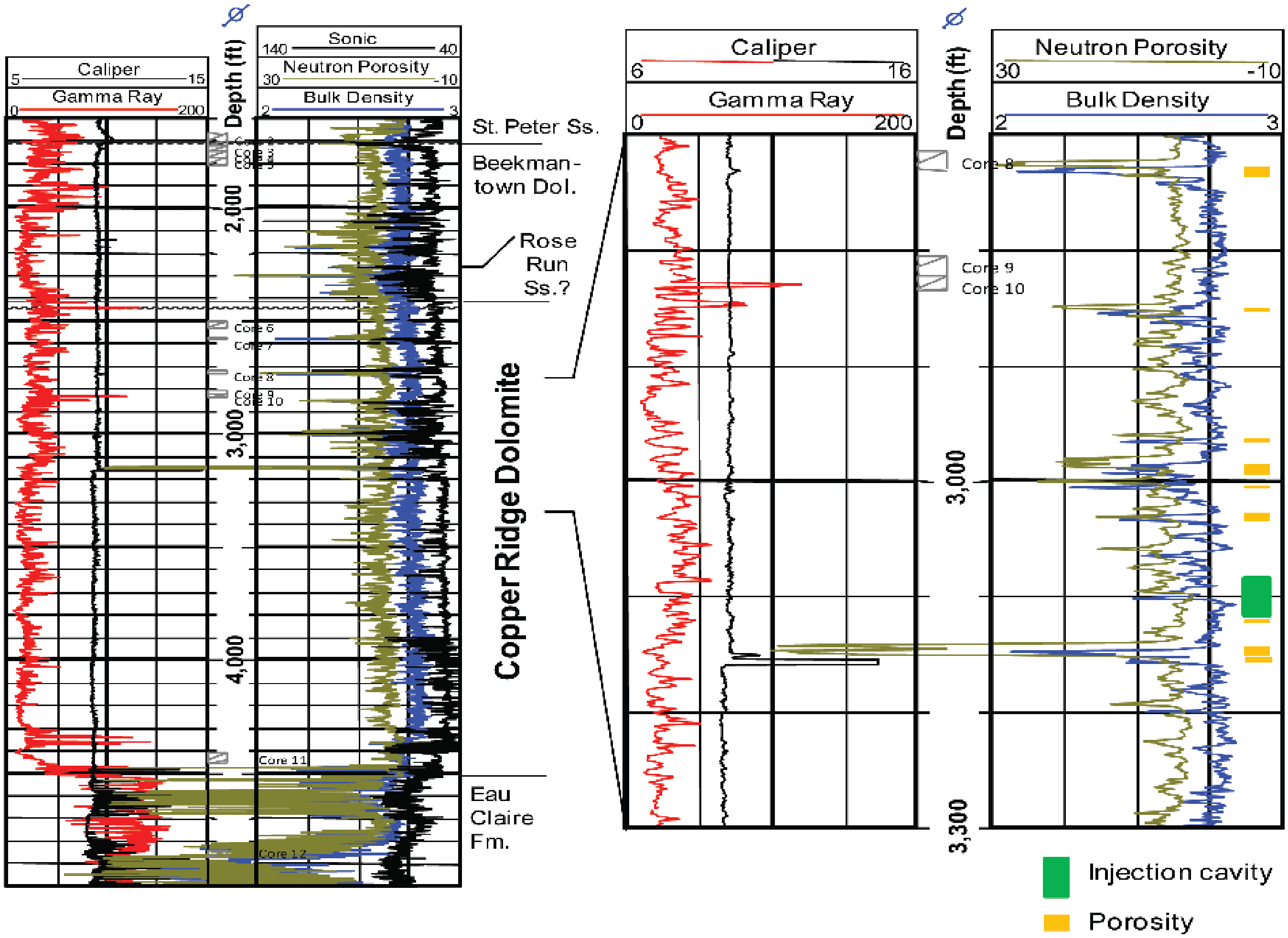

Figure 4.38. Geophysical log profile from the DuPont No. 1 WAD Fee well, Louisville, Ky. Expanded section shows discrete, narrow porosity zones and inferred injection zones in lower Knox (Copper Ridge) dolomites (arrows). From Greb and others (in press); depth to injection based on data in Clark and others (2005). Much thicker intervals of nonporous dolomite occur between porosity zones. Well location shown by red circle in Figures 4.36 and 4.37.

ry County, which also had gas shows in the Knox. An example of significant saltwater flow from the Knox is the 2,000 ft of salt water encountered from an interval with reported vuggy porosity in the Copper Ridge at 3,400 ft in the Ashland Oil and Refining No. 1 Caudill well in Rowan County (McGuire and Howell, 1963). In some wells, however, there is little or no significant porosity in the Knox, and consequently no hydrocarbons or water flows. Currently, KGS is working to determine if porous zones in the lower Knox are characteristic of specific stratigraphic intervals, and if so, if they are correlative over large areas. Development of such reservoir models will provide a valuable tool for hydrocarbon exploration and a more accurate estimate of storage potential in sequestration projects.

Western Kentucky Deep Porosity. Few wells penetrate the Copper Ridge in western Kentucky, but as an example, the Texas Gas No. 1 Kerrick (McLean County) shows a relatively thick zone with good porosity and apparent permeability (Fig. 4.40). Mean density porosity in the Copper Ridge in this porosity zone as calculated from logs is 9.3 percent (range 4 to 17 percent). The net thickness of the interval with more than 4 percent porosity is 54 ft. The net thickness with more than 10 percent porosity is approximately 16 ft. Although permeability is difficult to determine from standard geophysical logs, there are indications of permeability across this interval from the logs in this well. The hole diameter decreases across the porous interval (as indicated by the red infill on the caliper log in Fig-

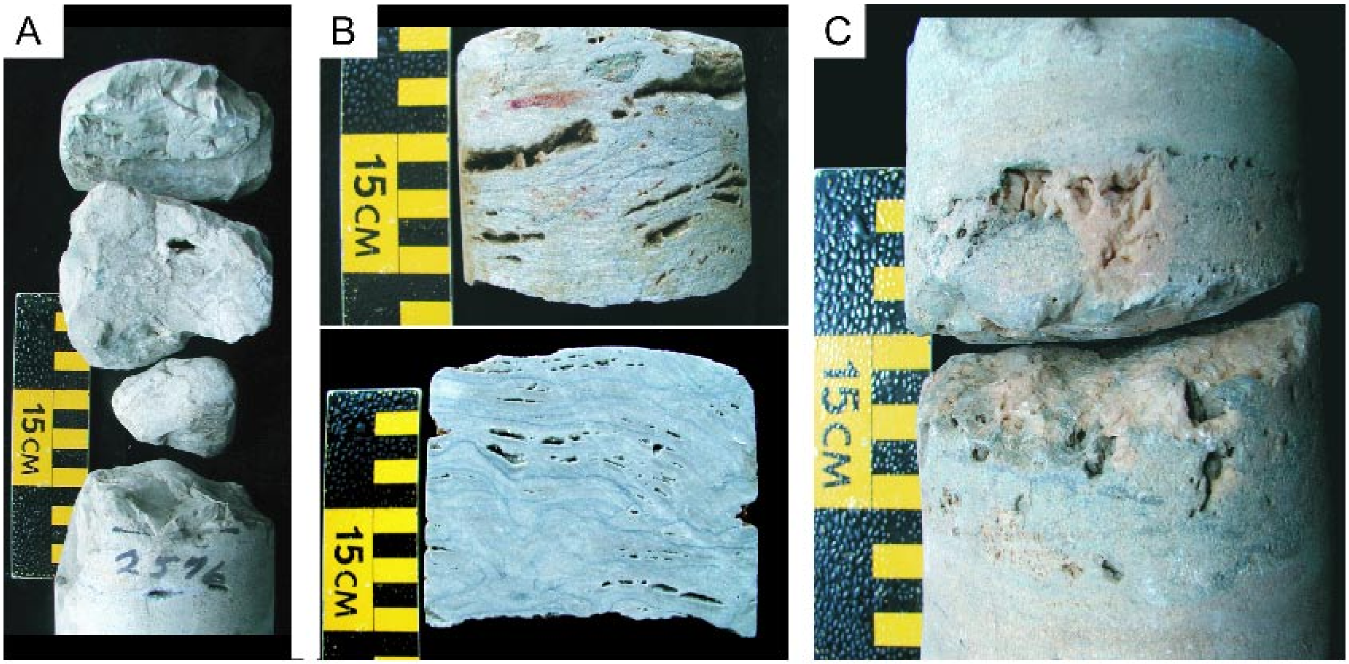

Figure 4.39. Various types of porosity in lower Knox (Copper Ridge) cores from the DuPont No. 1 WAD Fee well include (A) fractures with rounded margins, (B) moldic porosity in algal laminations from side of core and in cut section through core, and (C) solution vugs partly filled with saddle dolomite along a fracture. Well location shown by red circle in Figures 4.36 and 4.37.

ure 4.40), suggesting that drilling mud penetrated into the surrounding rock layer. Across the same interval, the resistivity logs separate, which is a characteristic invasion profile, meaning that drilling fluids entered pores in the surrounding rock.

The No. 1 Kerrick is 11 mi from Kentucky's proposed FutureGen site, and is the closest well with Copper Ridge data to the site. Using the aforementioned reservoir data from the Kerrick well, an injection depth of 7,380 ft (based on projection of porous zone from the Kerrick), and estimated reservoir temperature and pressure of 130°F and 3,203 psi (218 atm) (based on drillstem tests from the DuPont wells in Jefferson County), respectively, a calculated plume area of approximately 50 mi^2 would be generated by the injection of 1 million short tons of CO_2. This presumes that the reservoir indicated in the well is continuous across that area, which would require further testing. An estimated minimum of 10 wells with 200-ft spacing would be needed to safely inject that amount of CO_2 in a year (Commonwealth of Kentucky, 2006).

Hancock County CO_2 Injection Demonstration. The Kentucky Geological Survey No. 1 Marvin Blan well was drilled in Hancock County, Ky. (white square in Figures 4.36 and 4.37), in the summer of 2009 for the purpose of testing the Knox Group for carbon sequestration. The well was funded by the Kentucky Consortium for Carbon Storage with funding from Kentucky's House Bill 1 (August 2007), Peabody Energy, ConocoPhillips Co., E.ON U.S., Tennessee Valley Authority, Illinois Office of Coal Development, U.S. Department of Energy, National Energy Technology Laboratory, and others. According to Rick Bowersox of the Kentucky Geological Survey, the first injection test was a brine injection using straddle packers in a naturally fractured interval of the basal Copper Ridge from 7,180 to 7,455 ft. Two subsequent tests of the upper Copper Ridge failed shortly after pumping began because of communication around the packers through the formation's porosity system. Better injection tests were obtained through the use of a single packer and injecting into the full wellbore below. Injection rates of as much as 14 barrels per minute were achieved, with wellhead pressures of 285 to 550 psi.

CO_2 injection began on August 19, 2009. A total of 323 short tons of CO_2 were injected openhole into the upper and lower Knox at the pumping equipment maximum rate of 4.1 barrels/min. This was the first demonstration of CO_2 injection in the Knox in the United States. Temperature logs were run after injection to verify CO_2 placement. The wellbore was then flushed

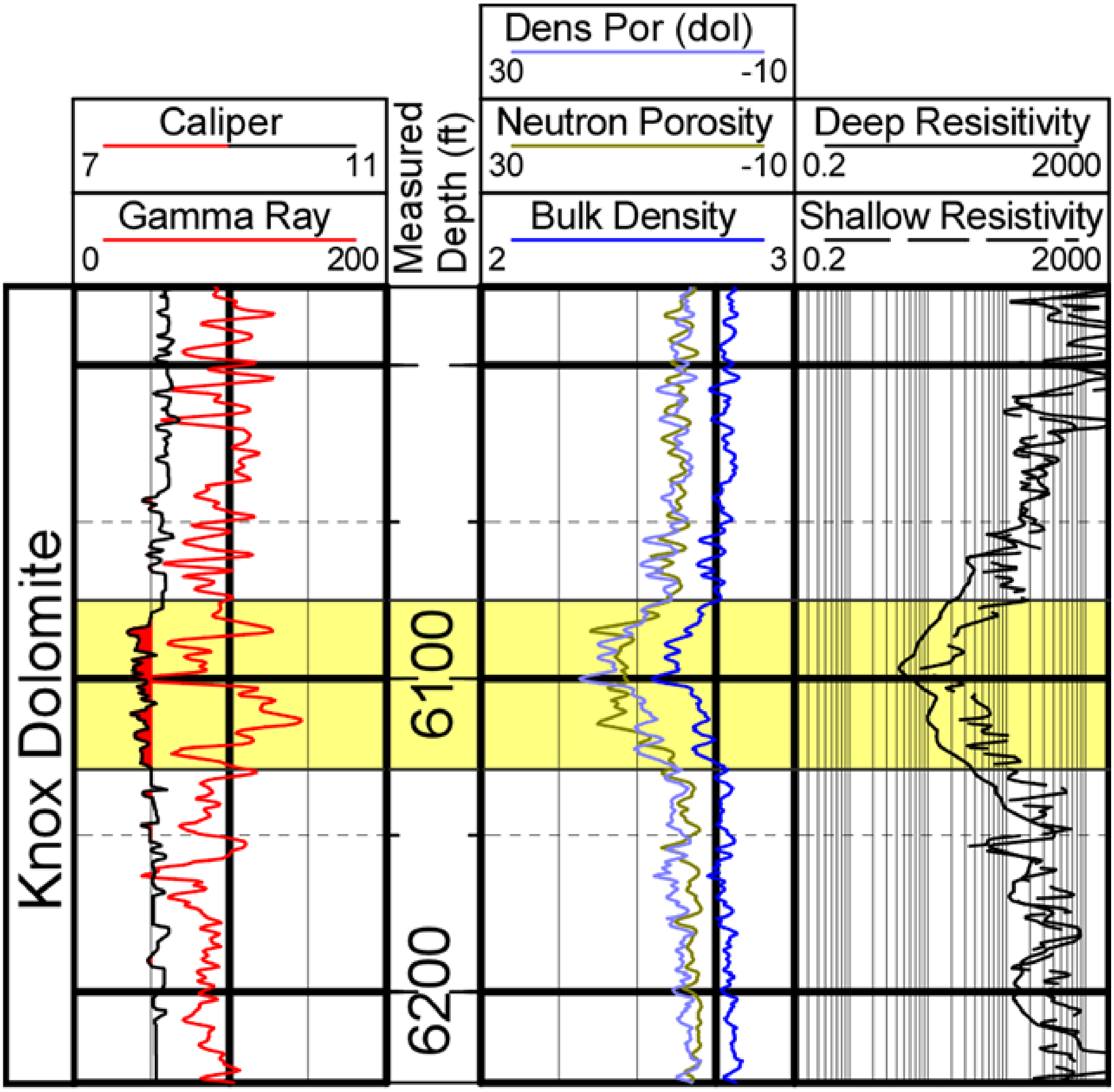

Figure 4.40. Geophysical log profile from the Texas Gas No. 1 Kerrick well in McLean County along the Rough Creek Fault System (northern margin of the Rough Creek Graben) showing thick porosity interval (yellow) in lower Knox (Copper Ridge) dolomite. The lateral extent of this zone is uncertain.

with brine and temporarily abandoned with downhole pressure monitoring in place, pending additional testing to be completed in early 2010. Final results and a report will be posted at the Kentucky Consortium for Carbon Storage Web site.

Further testing in the Blan well will be funded as part of a U.S. Department of Energy grant from the American Recovery and Reinvestment Act to the University of Illinois, Illinois State Geological Survey, and its partners, including the Kentucky Geological Survey. More information on this well can be found at the Kentucky Consortium for Carbon Storage Web site (www.uky.edu/KGS/Kentucky Consortium for Carbon Storage/).

Overlying Sealing/Confining Units. The overlying dense carbonates of the Knox would form the immediate seal of any lower Knox reservoir. Few wells penetrate this unit, especially in western Kentucky, so leakage up old wellbores should not be an issue. Stratigraphically higher confining intervals are the upper Knox, Middle Ordovician (Trenton–Black River) carbonates, the Upper Ordovician shales in the basins, and off of the Cincinnati Arch, the Devonian shales (Figs. 4.4–4.5).

CO_2 Storage Potential. The top of the lower Knox is less than 2,500 ft deep in parts of north-central Kentucky, so it would not be considered for large-volume carbon storage in those areas (shaded blue in Figure 4.37). Eastward into the Appalachian Basin and westward into the Illinois Basin, however, the unit is at an adequate depth for carbon storage, although in the deepest parts of these basins well costs may be too high for economic storage of carbon and porosity and permeability are uncertain.

A quantitative assessment of the storage capacity of the Copper Ridge has yet to be undertaken. Most of the potential saline reservoirs assessed in the region to date were extensive quartz-rich sandstones. The sandstones investigated are thought to be relatively homogenous, with similar grain sizes, cements, physical structures, and presumed porosity across large distances. In contrast, dolomites are generally heterogeneous, with varying cements and physical structures, and presumably porosity and permeability, across relatively short distances. This does not mean that dolomites won't be good storage reservoirs, just that they are more difficult to quantitatively assess and model than some of the regionally extensive sandstone reservoirs. Work is ongoing at KGS, the Kentucky Consortium for Carbon Storage, and regional DOE partnerships to further investigate this unit's potential. The Copper Ridge is one of two zones that will be used for storage at AEP's Mountaineer power plant in West Virginia. This plant is less than 50 mi east of Kentucky, so there should be similar-scale possibilities in Kentucky, and research at that site should be applicable to parts of eastern Kentucky. The success of the Kentucky Geological Survey No. 1 Marvin Blan well demonstration test and two waste-injection projects in west-central Kentucky provides optimism for this unit's carbon-storage capabilities in the western part of the state, although more research is needed before large-scale sequestration can be realized.

Secondary treatment was needed to provide adequate injection rates in the two waste injection wells in the unit and, possibly, adequate storage volume. Both injection projects also used openhole completions of thick sections of the Knox. Openhole completions may be needed to intersect several discrete porosity zones (vugular or fracture) in order to achieve the necessary net thickness for a large-volume storage project (if such completions are allowed by the EPA when rules for carbon storage are finalized). Having multiple injection zones might complicate monitoring of the CO_2 plumes, but would also result in a smaller plume since CO_2 would be distributed among multiple zones. More detailed analysis of treatment methods and issues related to openhole completions in Knox carbonate reservoirs may be required.

Rose Run–Gunter Sandstone (Middle Knox)

CO_2 unit type: possible regional/local reservoirs
KGS stratigraphic code: 368GNTR, 368RSRN
Series/system: Ordovician
Thickness: 0–220 ft
Distribution: eastern, central, and parts of western Kentucky
Number of wells with completion: 1(?)
Number of wells that TD: 28
Approximate number of wells drilled through unit: 203

Interval Definition. The Rose Run Sandstone is a sandy interval in the upper third of the Knox Group in parts of eastern and central Kentucky. The base of the Rose Run is the top of the Copper Ridge Dolomite and the top is the base of the Beekmantown Dolomite (Figs. 4.4–4.5). In western Kentucky (also in Missouri and southern Illinois), a sandstone at a similar stratigraphic position, called the Gunter Sandstone, is likely equivalent to the Rose Run. The Gunter extends from the top of the Eminence Dolomite to the base of the Gasconade Dolomite (Figs. 4.4–4.5).

The Gunter is variably developed in western Kentucky, and has only been identified in a few of western Kentucky's deep wells, including the Exxon No. 1 Duncan in Webster County, Maxus Exploration No. 1 James Ray and Shell Oil No. 1 Davis in Crittenden County, and Texas Gas Transmission No. 1 Shain in Grayson County. In the Shell Oil No. 1 Davis, several sandstones occur in a 400-ft interval near the top of the Copper Ridge. One sandstone has some porosity from 7,500 to 7,525 ft depth, and is described in the driller's log as a fine-grained, white to yellow (stained), cherty, and dolomitic sandstone. Elsewhere, the Gunter may be a sandy dolomite, rather than a true sandstone. Noger and Drahovzal (2005) reported thicknesses of 10 to 40 ft. Because of the paucity of deep data for the Gunter Sandstone in western Kentucky, much of this report concentrates on the Rose Run Sandstone in eastern Kentucky. The Gunter was tested in the Kentucky Geological Survey No. 1 Marvin Blan well, Hancock County, which will provide needed data on this interval in part of western Kentucky.

General Description. The Rose Run is a fine- to medium-grained (locally coarse-grained), quartzose, well-sorted sandstone with subrounded to rounded, clear to frosted grains and dolomitic cement. Freeman (1953) named the sandstone for a well in Bath County (red square in Figures 4.41 and 4.42) and described the sandstone in eight wells. McGuire and Howell (1963) provided sample descriptions from 10 wells, including a core description from the Ashland Oil and Refining No. 1 Wright well in Bath County.

In much of Kentucky, the Rose Run is interbedded with dolomite, and appears to grade westward and southward into the Knox dolomites, thinning or locally pinching out on the eastern margin of the Illinois Basin (Fig. 4.41). Because gradational contacts are common, picking the base and top of the unit can be difficult. Hence, the interval shown in the isopach map in Figure 4.41 includes sandstones, sandy dolomites, and dolomites with scattered sand grains rather than pure sandstone. Even where sandstones are developed, they may be interbedded with dolomites. Sandstone facies are best developed in northeastern Kentucky and the Rome Trough. The top and bottom of this interval has been inconsistently picked in the subsurface. In some areas, multiple sandy zones and interbedded dolomites have been included. In other areas, only one of several sandy zones has been identified as Rose Run. In many cases, detailed sample descriptions were needed to identify scattered quartz sand grains in dolostones as being Rose Run equivalents, even where porosity is developed. More work is needed in determining net sandstone and net porosity within this unit across Kentucky.

In eastern Kentucky, the Rose Run is thickest in Magoffin County, where it is in excess of 220 ft in

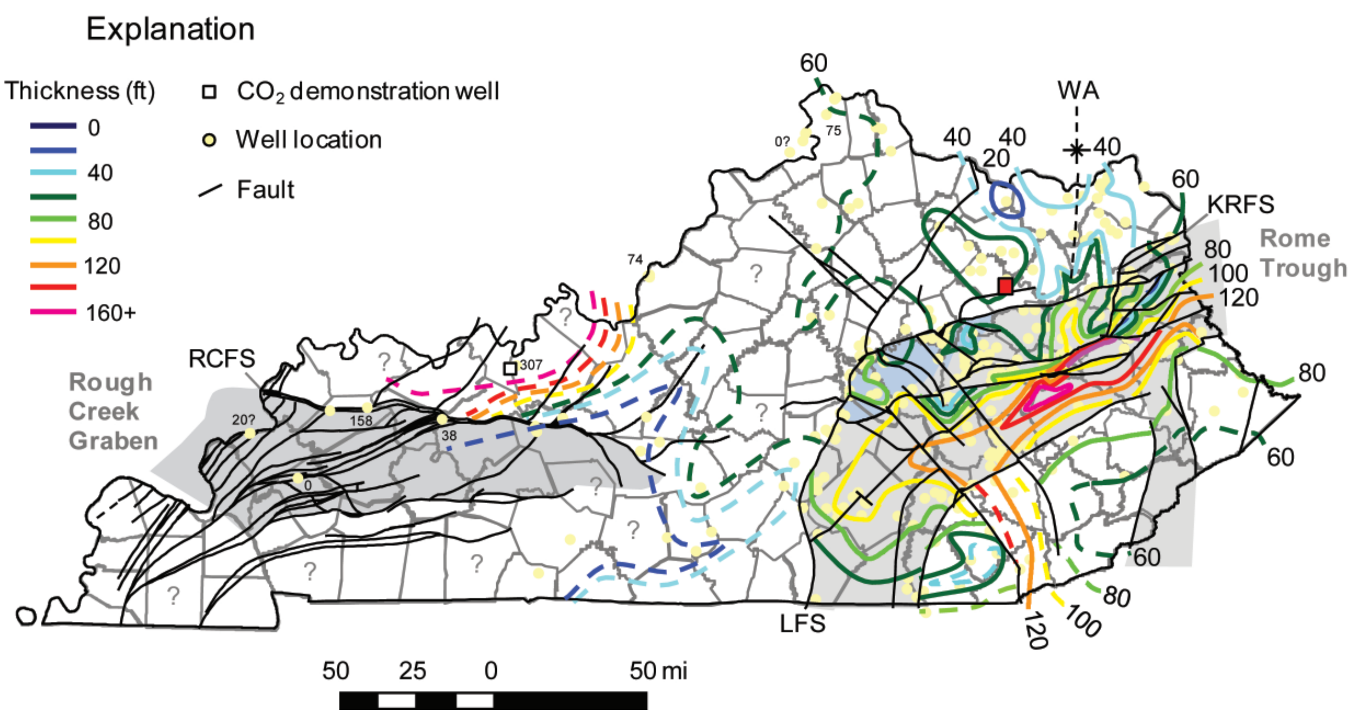

Figure 4.41. Thickness of the Rose Run Sandstone. In some of the areas shown the unit is a sandy carbonate rather than a sandstone. The thickness shown here is the thickness as previously picked on geophysical logs and does not indicate porosity or potential reservoir thickness. It may include nonsandstone units. Only a small part of this thickness and extent might be available for carbon storage. Structural grabens shown in gray. GF = Grenville Front. KRFS = Kentucky River Fault System. LFS = Lexington Fault System. RCFS = Rough Creek Fault System. WA = Waverly Arch. The discovery well in Bath County is shown as a red square.

fault blocks within the Rome Trough (Fig. 4.41). It also apparently thickens in Owen County in north-central Kentucky. In eastern Kentucky, the Rose Run is thinnest in Mason County (20 ft) near the crest of the Grenville Front and on the flanks of the Waverly Arch of Woodward (1961). In western Kentucky, the thickest reported Gunter (Rose Run) is 307 ft in the recently drilled Kentucky Geological Survey No. 1 Marvin Blan well in Hancock County (white square in Figure 4.41).

The Rose Run is shallowest (1,300 ft deep, 500 ft below sea level) above the Grenville Front and Lexington Fault System in Bourbon, Nicholas, and northern Clark Counties (Fig. 4.42). It is less than 2,500 ft deep across much of north-central and parts of south-central Kentucky. In eastern Kentucky it deepens gradually to the east to more than 9,300 ft (8,500 ft below sea level) in easternmost Pike County (Fig. 4.42). Westward, the interval deepens toward the Rough Creek Graben.

Known Reservoirs or Types of Porosity. Only one well in Kentucky has recorded a completion that might be in the Rose Run. The L&N Exploration No. 1 Arnett of Magoffin County has a 12-ft-thick porosity zone 417 ft below the top of the Knox (mistakenly reported as Black River on the well ticket). This zone may be the Beekmantown (upper Knox) rather than the Rose Run. The Arco No. 1 Duff well in Perry County had some gas shows in this Rose Run interval. Although oil or gas has not been produced from the Rose Run in Kentucky, large quantities of brine have been encountered in several deep wells in northeastern Kentucky, and the unit has apparent porosity indicated on downhole density logs in many wells.

In Ohio, oil production coincides with porosity in the Rose Run Sandstone where the overlying Beekmantown Dolomite is truncated by the Knox unconformity surface in areally restricted paleotopographic highs (Riley and others, 1993, 2002, 2003; Baranoski and others, 1996). Porosity in the Rose Run appears to result from leaching during development of the post-Knox unconformity. Although not completely truncated in northeastern Kentucky, the overlying Beekman-

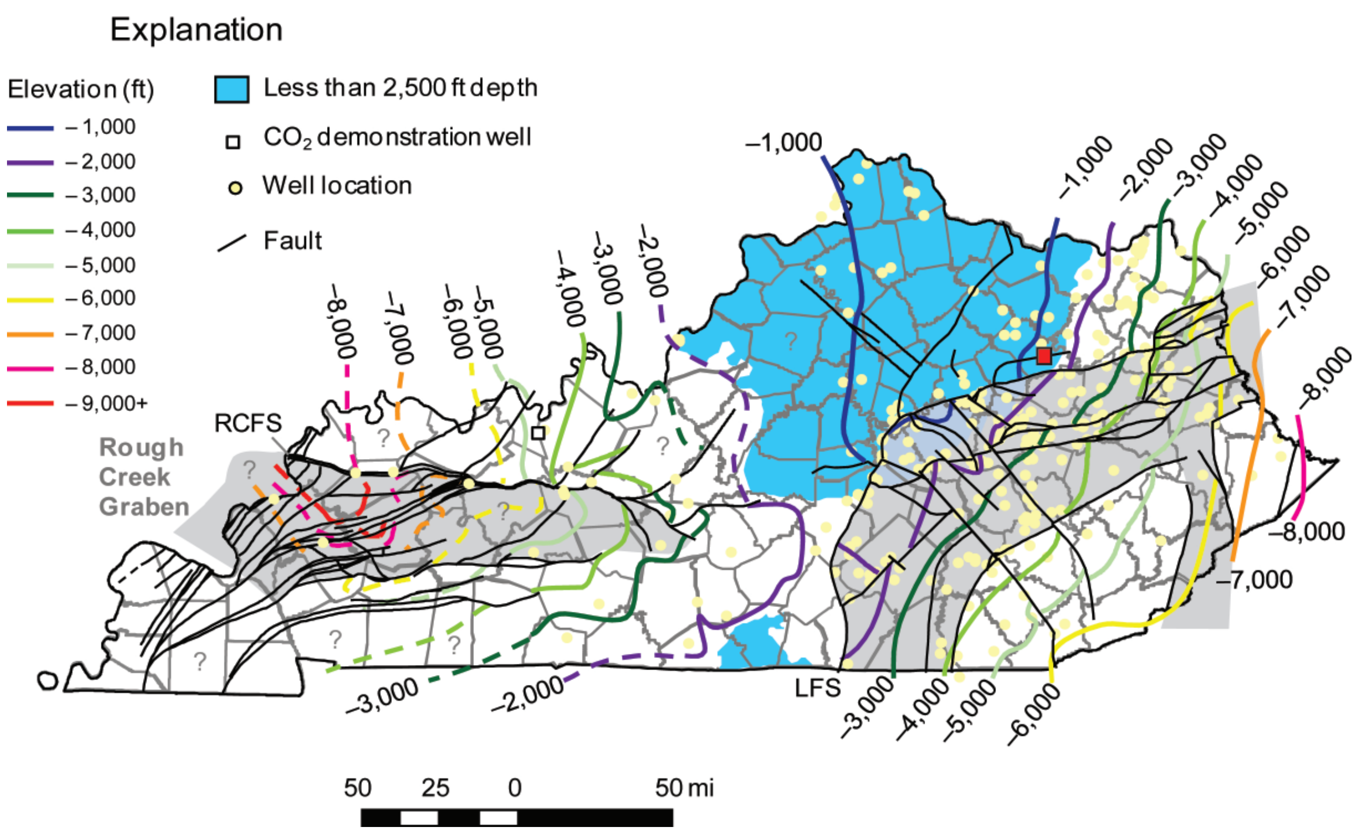

Figure 4.42. Structural elevation on top of the Rose Run Sandstone. Areas where the Rose Run is less than 2,500 ft deep are shaded in light blue. Overall distribution of Rose Run is shown in gray. The discovery well in Bath County is shown as a red square.

town thins in Carter, Elliott, Lawrence, Johnson, and Rowan Counties along the Waverly Arch. In this area there appears to be significant porosity in the Rose Run resulting from leaching similar to that in Ohio. For example, core analyses from the Rose Run at a depth of 2,021 to 2,047 ft in a well in Bath County showed 12 to 18 percent porosity and permeability of 100 to 625 md (McGuire and Howell, 1963). The Friestadt No. 1 Wright well, Rowan County, also reported 1,750 ft of water produced from the Rose Run at a depth of 2,018 ft, and according to McGuire and Howell (1963), large volumes of water have been encountered in the Rose Run in several northeastern Kentucky counties. Also, upriver in West Virginia, the Rose Run is one of two zones that are planned to be used for carbon storage at AEP's Mountaineer power plant.

Hancock County CO_2 Injection Demonstration. The Kentucky Geological Survey No. 1 Marvin Blan well was drilled in Hancock County, western Kentucky (white square in Figures 4.41 and 4.42), in the summer of 2009 for the purpose of testing the Knox Group for carbon sequestration. According to Rick Bowersox of the Kentucky Geological Survey, the Beekmantown, interbedded Gunter Sandstone, and uppermost section of the underlying Copper Ridge were identified as the principal reservoirs in the well. In the well, the Gunter was penetrated from 5,090 to 5,230 ft, and was interbedded with the Beekmantown Dolomite. The Gunter is composed of fine-grained, well-rounded quartz sand in a dolomite matrix interbedded with thin dolomites. Sandstone comprises 90 ft or 64 percent of the 140-ft-thick section. Planar bedding and herringbone cross-beds were observed in core recovered from the uppermost 32 ft of the Gunter. Dolomite interbeds were characterized by vuggy porosity developed in fabric-destructive dolomites, solution-enhanced fractures, and pervasive styolites. Two porosity systems are developed: intergranular porosity in the sandstones, averaging 11.5 percent, and the dolomite complex, averaging 3.5 percent porosity.

Openhole injection tests of brine below a single packer at the top of the Knox were able to inject 18,454 barrels of brine and borax solution into the upper Knox, Gunter Sandstone, and lower Knox, at rates of as much as 14 barrels/min, with wellhead pressures of 285 to 550 psi. Temperature logs showed that 70 percent of the injected brine went into the upper Knox and Gunter Sandstone. Injection of a borax tracer solution and monitoring with pulsed neutron and spinner logs confirmed these results. Final results and a report will be posted on the Kentucky Consortium for Carbon Storage Web site.

CO_2 injection began on August 19, 2009. A total of 323 tons of CO_2 were injected into the Gunter Sandstone and Knox carbonates at the pumping equipment maximum rate of 4.1 barrels/min. This was the first demonstration of CO_2 injection in the Gunter in the United States. Further testing will be funded as part of a U.S. Department of Energy grant from the American Recovery and Reinvestment Act to the University of Illinois, Illinois State Geological Survey, and its partners, including the Kentucky Geological Survey.

Overlying Sealing/Confining Units. The dense carbonates of the upper Knox would form the immediate seal of any Rose Run or Gunter reservoir. Few wells penetrate the Rose Run–Gunter, so leakage up old wellbores should not be an issue. Stratigraphically higher confining intervals are the upper Knox, Middle Ordovician (Trenton–Black River) carbonates, Upper Ordovician shales, and Devonian shales (Figs. 4.4–4.5). Riley and others (2003) indicated that in the absence of open fractures or faults, an effective confinement zone is present above the Rose Run Sandstone for CO_2 sequestration.

CO_2 Storage Potential. The top of the Rose Run is less than 2,500 ft deep in much of central Kentucky so would not be considered for large-volume carbon storage in those areas (shaded blue in Figure 4.42). Thinning of the Rose Run to the west precludes storage in some parts of the Illinois Basin of western Kentucky, although the interval shows some porosity north of the Rough Creek Fault System, and was successfully tested in the Kentucky Geological Survey No. 1 Marvin Blan well in Hancock County, Ky. Eastward, the Rose Run is at adequate depths for carbon storage in the Rome Trough and southeastern Kentucky. The Rose Run was calculated to cover an area of approximately 13,000 mi^2 in eastern Kentucky and have a potential volumetric storage capacity of 60 billion short tons (54.44 billion metric tons) according to the phase I report of the Midwest Regional Carbon Sequestration Partnership (Wickstrom and others, 2005). If 10 percent of that volume is accessible, there would be 6.0 billion short tons (5.4 billion metric tons) of storage, and if the accessible volume is reduced to 1 percent, then 0.6 billion short ton (0.5 billion metric ton) would be available. Conservative estimates are probably best with this unit, since it is a sandy carbonate or interbedded sandstone and carbonate, rather than a homogeneous sandstone across much of its distribution. Because the Rose Run is a sandy carbonate or sandstone interbedded with carbonates, porosity intervals may not be connected across wide areas. Similar estimates have not been completed for the Gunter Sandstone in western Kentucky.

The Rose Run–Gunter Sandstone is situated between the upper and lower Knox carbonates, so that if porosity is found in the Rose Run–Gunter in an area, it might be possible to use openhole completions that include porosity zones in the Rose Run and over- and underlying carbonates (if such completions are allowed by EPA when rules for carbon storage are finalized). An openhole completion was used in the Kentucky Consortium for Carbon Storage's demonstration well in Hancock County, Ky. As previously noted, injection into multiple zones might complicate monitoring of the CO_2 plume, but it would also reduce the plume size over which monitoring needed to occur. There are no areas of current gas production from the Rose Run–Gunter in Kentucky, so there should not be issues related to interference with existing energy resources.

Upper Knox Carbonates

CO_2 unit type: possible regional/local reservoirs and secondary confining unit
KGS stratigraphic code: 368BKMN, 368KNOX, 368KNOXU
Series/system: Ordovician
Thickness: 134–4,200 ft
Distribution: statewide
Number of wells with completion: 43–3,281[1]
Number of wells that TD: 11,261[2]
Approximate number of wells drilled through unit: 231

Interval Definition. The upper Knox interval includes all strata between the top of the Rose Run–Gunter Sandstone, or the top of the Copper Ridge Dolomite where the Rose Run–Gunter is absent, to the post-Knox unconformity. The unconformity is overlain by the St. Peter Sandstone or Wells Creek Formation where the St. Peter is missing (Figs. 4.4–4.5). In most of Kentucky this interval is equivalent to the Beekmantown Formation. In far western Kentucky it is equivalent to the Jefferson City, Roubidoux, and Gasconade dolomites of Missouri or the Shakopee and Oneota Dolomites of southern Illinois. In the Jackson Purchase Region, the upper Knox includes the Cotter Dolomite, which is truncated beneath the post-Knox unconformity eastward (Figs. 4.4–4.5). The Cotter is younger than the Beekmantown to the east. The Cotter is overlain by the Everton Dolomite. An unconformity below the Everton merges with the unconformity at the base of the St. Peter Sandstone east of the Jackson Purchase where the Everton is absent (Schwalb, 1968; Noger and Drahovzal, 2005) to form the post-Knox unconformity across most of Kentucky (Figs. 4.4–4.5). The Everton is lithologically similar to the Knox, so distinguishing the two is often difficult. For this investigation, the Everton and Cotter are included with the upper Knox interval.

The post-Knox unconformity at the top of the interval is a well-studied regional unconformity (Sloss, 1963; Skinner, 1971; Mussman and Read, 1986; Mussman and others, 1988; Smosna and others, 2005). The unconformity is overlain by the St. Peter Sandstone or the overlying limestones and dolomites of the Wells Creek Formation where the St. Peter Sandstone is absent. Significant relief (more than 100 ft locally) occurs along the upper contact. In south-central Kentucky, dolomitization of some of the overlying Wells Creek limestones can complicate picking the top of the Knox.

The base of the Knox is the Rose Run–Gunter Sandstone or where absent, the top of the Copper Ridge Dolomite. The upper-lower Knox contact is difficult to pick on geophysical logs where the Rose Run is absent, or where sample descriptions are not available for determining the position of sand grains in Rose Run–equivalent strata. Where the sandstone is absent, the base of the upper Knox (Beekmantown) is generally placed where density-log signatures change from more consistent dense dolomite (Copper Ridge) to more variable density dolomite (Beekmantown).

General Description. The upper Knox (Beekmantown Dolomite) is a tan, light brown to gray, finely to coarsely crystalline, cherty dolomite interbedded with thin layers or laminations of pale green to green-gray bentonitic and dolomitic silty shales and siltstones

[1]Forty-three wells are specifically identified as upper Knox completions, but the majority of the 3,281 Knox completions (unspecified as to what part of the Knox they are from) are from the upper Knox.
[2]Although more than 11,000 wells TD in the Knox, most are at shallow depths in south-central Kentucky on the Cincinnati Arch. In eastern Kentucky, 501 wells TD in the upper Knox, and 37 wells TD in the upper Knox in western Kentucky.

(McGuire and Howell, 1963; Sutton, 1981). In western Kentucky, descriptions of upper Knox penetrations are included in the sample descriptions of the Conoco No. 1 Turner well, McLean County; the Exxon No. 1 Duncan well, Webster County; and the Texas Gas Transmission No. 1 Shain well, Grayson County. These descriptions can be accessed online at the Kentucky Geological Survey's Oil and Gas Database. Sample descriptions from 12 wells in eastern Kentucky are provided in McGuire and Howell (1963). Additional descriptions can be found in Freeman (1951). In south-central Kentucky, numerous descriptions of the upper Knox from core and samples are provided in published reports on oil and gas fields (Perkins, 1970; Norris, 1981; Anderson, 1991; Gooding, 1992).

The Beekmantown is thinnest in eastern Kentucky in Carter, Elliott, Lawrence, and Johnson Counties, in the Waverly Arch (Fig. 4.43) (Woodward, 1961; Sutton, 1981). The thickest the upper Knox reaches in eastern Kentucky is 1,200 ft in southwestern Laurel and southeastern Pulaski Counties (Fig. 4.43). In western Kentucky, thickness varies considerably in the Beekmantown north of the Rough Creek Fault System (black line on northern border of the Rough Creek Graben in Figure 4.43). The upper Knox is less than 200 ft thick in Henderson County, which corresponds to an area in which the overlying St. Peter Sandstone thickens, so thinning may be partly the result of erosion beneath the St. Peter. Other areas of variation in the graben east of Henderson County may be caused by faulting or paleotopographic variation on the upper Knox unconformity surface. In light of the apparent influence faults have on thickness, faulting (and related fractures) likely also influenced paleotopography on the post-Knox unconformity surface. South of the Rough Creek Fault System, in the Rough Creek Graben (shaded gray in Figure 4.43), the upper Knox interval may be more than 4,800 ft thick on the western end

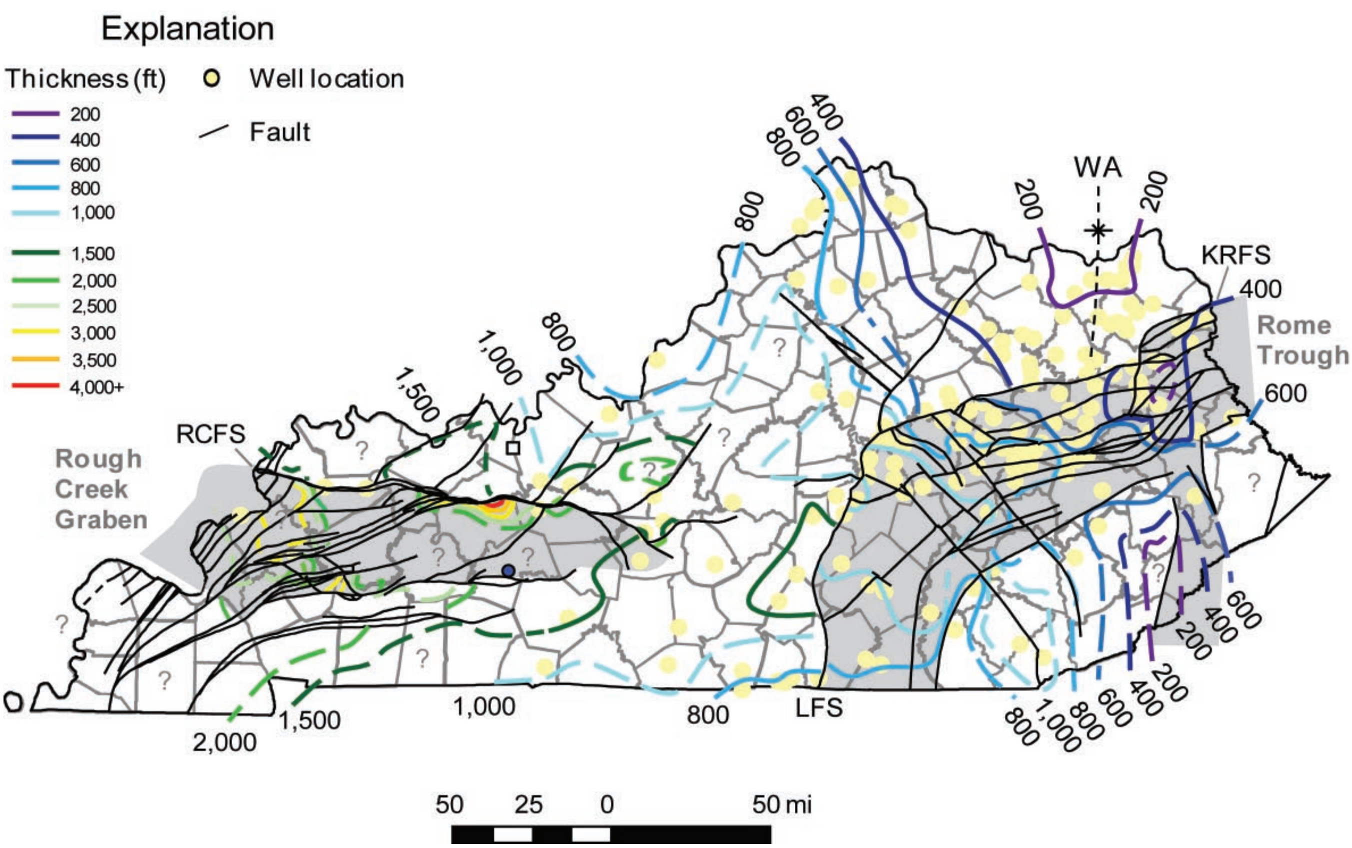

Figure 4.43. Thickness of the upper Knox interval in Kentucky. The thickness shown for this interval does not indicate porosity or potential reservoir thickness. Only a small part of this thickness and extent might be available for carbon storage. Deep grabens are shaded gray. Thicknesses in western Kentucky, especially within the Rough Creek Graben, are uncertain because there are few wells and the lower and upper Knox are difficult to differentiate through seismic analysis. Contour interval is 200 ft in eastern and central Kentucky and 500 ft in western Kentucky. The blue circle is the IMCO Recyling injection well in Butler County. KRFS = Kentucky River Fault System. LFS = Lexington Fault System. RCFS = Rough Creek Fault System. WA = Waverly Arch.

of the graben in Livingston County where the Everton part of the interval thickens. Eastward, in the main part of the graben, the thickness of the upper Knox (Beekmantown) is uncertain because (1) of few wells and (2) the upper and lower Knox are difficult to differentiate on seismic analyses. Isopach lines have not been drawn on the map for several counties within the graben because of this uncertainty. The total Knox interval thickens to more than 7,000 ft in the Rough Creek Fault System along the northern margin of the graben. Noger and Drahovzal (2005) showed that the Beekmantown part of the upper Knox interval also thickens from east to west, from approximately 1,500 to 2,650 ft, within the Rough Creek Fault System and in wells just south of the fault system.

In areas of dense drilling in south-central Kentucky, the top of the Knox has considerable relief (100 to 150 ft) between wells. Similar relief may characterize this surface basinward, especially on the shelves bounding the deeper grabens, which cannot be currently detected because so few wells have been drilled into this interval in western Kentucky. Any potential thickness variation would be very local, and would be superimposed on the larger regional thickness trends shown in Figure 4.43. It is also possible that structural relief on the unconformity diminishes into the basins, in which case stratigraphic and structural traps like those encountered in south-central Kentucky would not be encountered deeper in the basins.

In central Kentucky, the upper Knox is shallowest (600 to 900 ft below the surface, 300 ft above sea level) just west of the intersection of the Lexington and Kentucky River Fault Systems in Jessamine County (Fig. 4.44). This is the apex of the Jessamine Dome, a structural high along the Cincinnati Arch. The upper Knox is less than 2,500 ft deep across the central third of the state on either side of the arch, and in parts of the Jackson Purchase Region (far western Kentucky). Eastward from the Cincinnati Arch, the top of the Knox deepens to 7,500 ft below sea level in Pike County, with relatively small offsets along some of the major faults. Many of the faults that influenced earlier

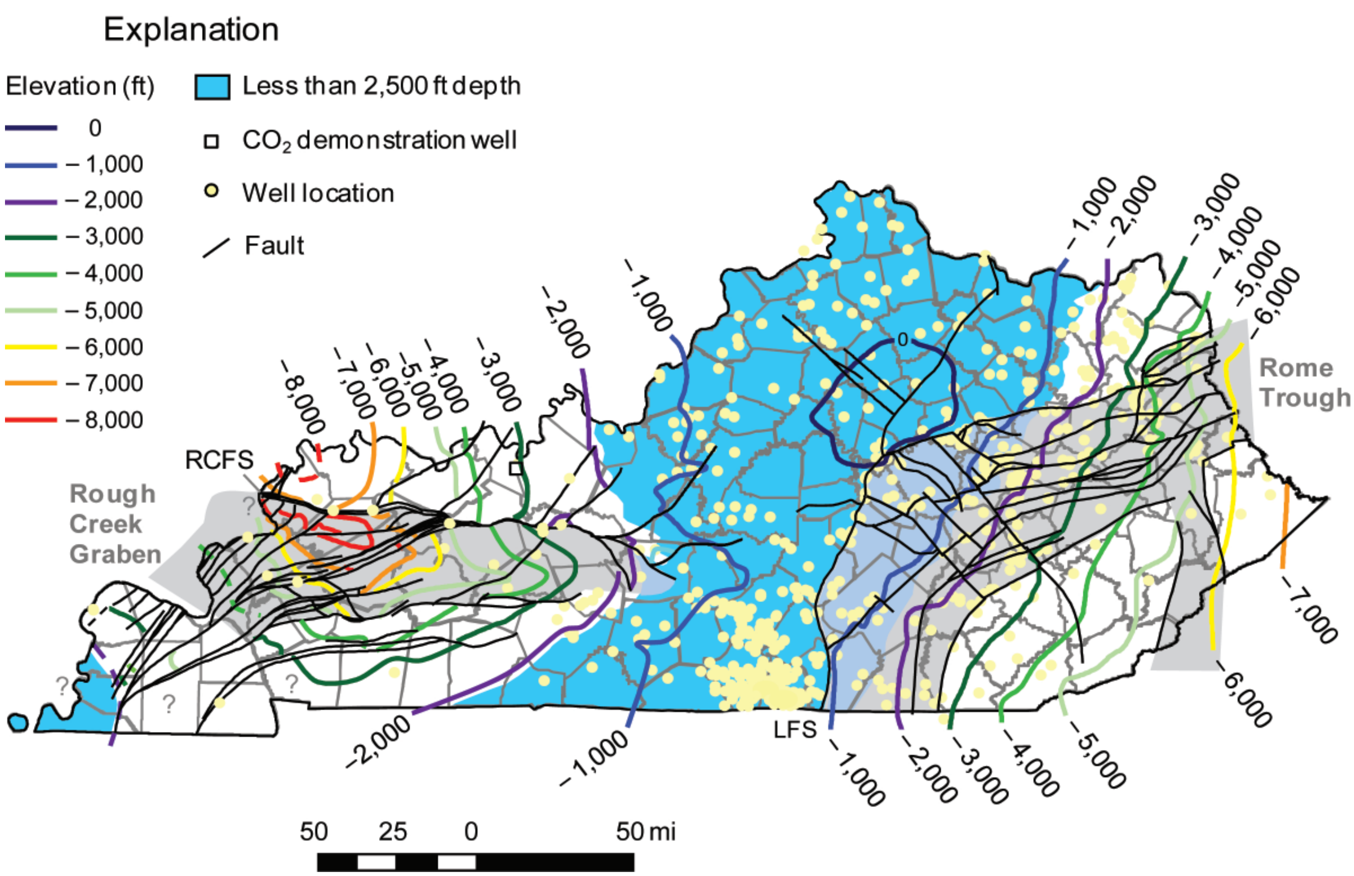

Figure 4.44. Structural elevation on top of the upper Knox interval. This is the Knox unconformity surface across most of the state. Areas less than 2,500 ft deep are shaded blue. Deep grabens are shaded gray. Elevations in western Kentucky are partly based on preliminary seismic interpretations from Jim Drahovzal (Kentucky Geological Survey). LFS = Lexington Fault System. RCFS = Rough Creek Fault System.

sedimentation may not reach to the top of the Knox, but are shown in Figures 4.43 and 4.44 in case they do extend to (or through) the top of the Knox. Westward, the upper Knox gradually deepens toward the Rough Creek Graben and then rapidly deepens into the graben and west of the graben. Some variations in thickness appear to correspond to faulting, suggesting possible fault control of thickness (Fig. 4.43).

The top of the Knox is 9,300 ft below the surface (9,000 ft below sea level) in western Union County, just south of the Rough Creek Fault System (Fig. 4.44). Offset is 1,400 ft across the fault system. Within the graben in southern Hopkins County is a small fault block with 2,600 ft of offset. On the southern border of the graben, dips are more gradual, with 200 to 600 ft of offset across the southern bounding faults.

Known Reservoirs or Types of Porosity. Porosity is significant but highly variable in the upper Knox. Some wells have numerous porosity zones, whereas others have none. Much of the known porosity is associated with the post-Knox unconformity. Porosity within 150 ft of the unconformity results from a complex diagenetic history that included multiple periods of exposure and erosion during formation of the unconformity, and multiple periods of fluid flow from the basins (Jolly and Heyl, 1964; Skinner, 1971; Kyle, 1976; Mussman and others, 1988; Anderson, 1991; Montanez, 1994; Riley, 2001; Smosna and others, 2005; Greb and others, in press). At least 43 wells are reported to have had completions in the Beekmantown (upper Knox), but 3,238 wells have reported completions in the Knox, and most (if not all) of these are from the upper Knox (Fig. 4.45).

A porous sandstone to sandy dolomite called the Knox sand or Knox stray by drillers has been locally reported in the upper 100 ft of the Knox by drillers in

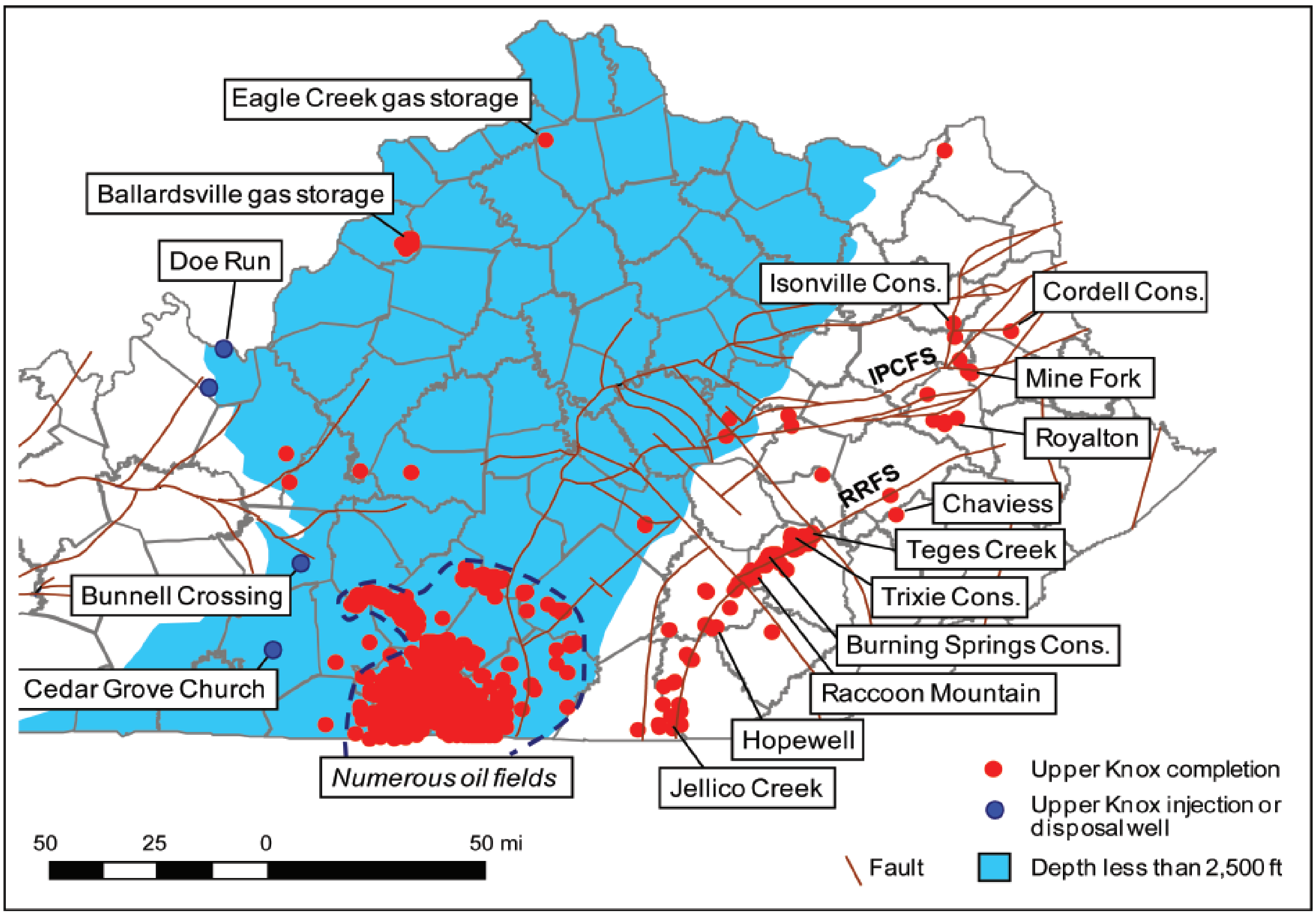

Figure 4.45. Kentucky wells with reported completions in the upper Knox interval. There are more than 3,000 wells with reported completions in the oil fields of south-central Kentucky. IPCFS = Irvine–Paint Creek Fault System. RU = Rockcastle Uplift. See Table 4.3 for more information on completions at depths of more than 2,500 ft.

north-central Kentucky from Bullitt to Boone Counties. Because the sandstone occurs in the uppermost Knox where it is truncated by the post-Knox unconformity, it can be confused with the overlying St. Peter Sandstone. In some cases, the sandstone was interpreted as the St. Peter Sandstone and overlying dolomites were interpreted as dolomitized Wells Creek Formation. Knox-like dolomites are known from above the sandstone, however, so it likely is a locally developed sandstone in the upper Knox Beekmantown Formation. Porosity is known from Knox stray sands in the Ballardsville Field (see description below). Porosity was also encountered in an upper Knox sandstone (likely the same stray sand) in the recently drilled Battelle No. 1 Duke Energy East Bend Station well in Boone County. More research is needed on the distribution and characteristics of this stray Knox sandstone.

Gas Storage Fields. The upper Knox has been successfully used for gas (methane) storage in several fields in northern Kentucky (Fig. 4.45) and southern Indiana at shallow depths (less than 1,000 ft). All of the gas storage fields are paleotopographic highs on the Knox unconformity surface (Keller and Abdulkareem, 1980; Keller, 1998). These fields tend to be small in area (Fig. 4.46), similar to the sizes of oil and gas fields

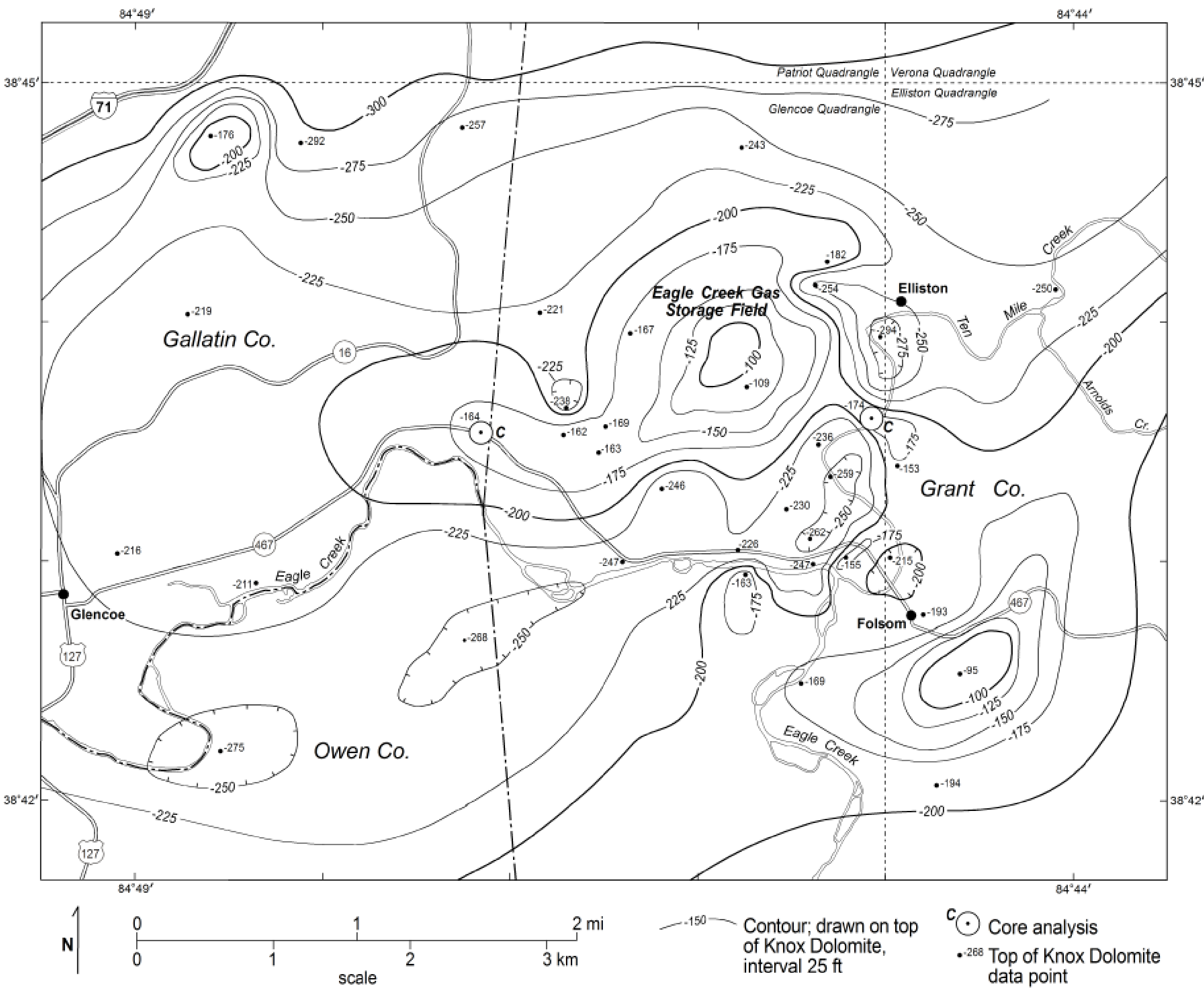

Figure 4.46. Structure on top of the Knox in the Eagle Creek gas storage field, showing a typical paleotopographic high on the post-Knox unconformity surface in central Kentucky. Datum is sea level. Map by Warren Anderson (Kentucky Geological Survey). See Figure 4.45 for location of the field.

on the Knox unconformity surface. Greb and others (in press) summarized core analyses from the Eagle Creek Field of Grant County (Fig. 4.47). In the Eagle Creek Field, porosities range from 3 to 18 percent. The average horizontal permeability is 202 md, with a range from less than 1 to 5,270 md. Many of the very high-permeability zones may be related to fractures, which were noted in one well. Several zones of porosity (average of 12 percent) are present at 755 and 765 ft, with an average permeability of 620 md. These porous and permeable zones are approximately 35 ft below the unconformity and probably represent a paleoaquifer. Although reservoir storage capacity data are not available for this field, gas storage fields along the unconformity in Indiana have gas (methane) storage capacities of 0.49 to 1.39 mcf.

In the Ballardsville Field, Oldham County (Fig. 4.45), porosity is developed within 60 ft of the post-Knox unconformity surface. Forty-two wells have reported completions in the field at depths from 1,240 to 1,430 ft. The field is located along the Ballardsville Fault, so the reservoir is a stratigraphic-structural trap. Multiple zones of gas and water were encountered in the upper Knox in several wells. In this field, a sandstone at the top of the Knox, called a Knox sand, may be an upper Knox sand, the overlying St. Peter Sandstone, or a combination of both sandstones. Numerous wells in counties southwest of the Ballardsville Field (Oldham, Nelson, Spencer, Bullitt, Hardin) had holes fill with salty, sulfur-smelling water below the top of the Knox in what was reported as "water sands" on most drillers' logs. Several wells with detailed sample descriptions indicate these water sands were actually dolomites with abundant grains of quartz sand in the upper Knox. If the various water sands indicated by drillers are the same porosity zone, they indicate a broad sandy saline reservoir in the upper Knox. This reservoir is too shallow for miscible carbon storage in this area (1,200 to 1,600 ft depth), but it provides evidence of a large-area porosity zone in the upper Knox. More work is needed on the distribution of this sandy zone to determine if it extends west, where this interval would be at depths of more than 2,500 ft.

Oil Fields of South-Central Kentucky. The upper Knox produces from paleotopographic highs (buried hills) on the Knox unconformity surface in numerous fields at shallow depths in south-central Kentucky (Fig. 4.45) (Anderson, 1991; Gooding, 1992). These fields are located across the crest of the Cincinnati Arch. Most of the more than 150 producing Knox fields produce from the uppermost part of the Knox. Reports of typical fields can be found in Perkins (1970) and Norris (1981). Four porosity zones have been recognized in the upper Knox (Perkins, 1970; Norris, 1981). It is uncertain if similar zones can be found in the basins, off of the arch.

Eastern Kentucky Deep Oil and Gas. At least 19 eastern Kentucky upper Knox fields have reported completions at depths of more than 2,500 ft (Table 4.3). Two to three fields have had significant production. Many other wells into the upper Knox have encountered water. Salt water is especially common at or beneath the unconformity surface at the top of the Knox, which indicates the possibility of an extensive saline aquifer.

The deepest completions are in the Chavies Field of Perry County at depths of 5,390 to 5,484 ft, and the Cordell Field of Lawrence County at depths of 5,337 to 5,571 ft (Fig. 4.45, Table 4.3). Both fields found minor hydrocarbons in multiple thin porosity zones within 250 ft of the top of the Knox. Sample descriptions are available from the Arco Exploration No. 2 Duff well of the Chavies Field in the Kentucky Geological Survey Oil and Gas Database.

The largest number of deep Knox completions are in the Burning Springs Field of

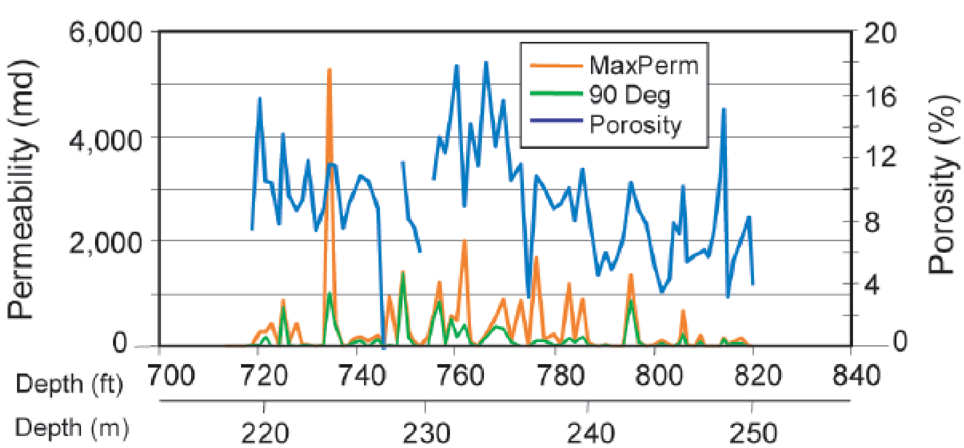

Figure 4.47. Porosity, horizontal, and vertical permeability in the upper Knox (Beekmantown Formation) as reported from analyses of samples in the Union Light Heat and Power No. 2 Thomason well in the Eagle Creek gas storage field, Kentucky.

Table 4.3. Upper Knox fields with reported completions deeper than 2,500 ft, arranged by depth. Geophysical logs and well records for these completions can be viewed online at the KGS Oil and Gas Database.

No. of Wells with Completions	*Depth (ft)*	*Example KGS Record Nos.*	*Field*	*County*
2	5,390–5,484	16169, 68179	Chavies	Perry
1	5,337–5,511	11508	Cordell Consolidated	Lawrence
1	4,920	121995	Isonville Consolidated	Elliott
1	4,898	130969	unnamed	Magoffin
1	4,809–5,068	112282	unnamed	Breathitt
1	4,790–4,794	14808	Moon	Morgan
1	4,710	128460	Gose School	Magoffin
1	4,500–4,747	49943	Mima	Morgan
6	4,480–4,830	26154, 41558, 51571	Mine Fork	Johnson
1	4,475	103150	Green Branch	Knox
3	4,441–5,450	128248, 130314, 131136	Royalton	Clay
1	3,899	113891	Jellico Creek North	Whitley
1	3,896–3,994	123151	unnamed	McCreary
1	3,830–3,835	113890	Kidd School	McCreary
4	3,816–3,910	74428, 127011, 127012	Oneida Consolidated	Clay
1	3,750–3,984	126527	unnamed	McCreary
2	3,706–3,738	76769, 79207	Woodbine Consolidated	Whitley
1	3,707–3,711	27165	Roaring Paunch	McCreary
1	3,688–3,705	49000	Little Goose	Clay
1	3,680–3,690	84012	Frankford School	Whitley
7	3,661–3,905	106454, 106982, 108173	Jellico Creek	McCreary, Whitley
11	3,620–3,891	51127, 69932, 86365	Trixie Consolidated	Clay
14	3,605–3,850	50224, 67894, 37560	Teges Creek	Clay
1	3,596–3,630	128891	unnamed	Clay
1	3,594–3,596	105427	Lynam Creek	Owsley
2	3,590–3,720	106819, 106857	Midsprings School	Whitley
1	3,570–3,575	109743	Williamsburg Cons.	Whitley
1	3,537–3,598	8593	Pilot	Estill
1	3,510–3,520	105258	Happy Hollow	Laurel
3	3,500–3,754	83305, 88480, 84147	Corbin Northwest	Whitley
1	3,473–3,491	66850	unnamed	Greenup
3	3,450–3,920	83116, 114474, 114484	Hopewell	Laurel
4	3,372–3,734	70640, 76220, 81805	Fogertown	Clay
1	3,330–3,568	38871	Big Sinking	Lee
1	3,188–3,198	11440	Baldrock	Laurel
73	3,168–4,001	60162, 62224, 66390	Burning Springs Cons.	Clay
1	3,000–3,010	114665	unnamed	Larue
1	2,999–3,212	123552	unnamed	Meade
21	2,939–3,730	35277, 3456, 3458	Raccoon Mountain	Clay, Laurel

Clay County and the adjacent Raccoon Mountain Field of Clay and Laurel Counties (Fig. 4.45, Table 4.3). In both fields, several wells produce from a porous zone within 250 ft of the post-Knox unconformity. Production occurs along an elongate trend above the Rockcastle River Uplift (RRU in Fig. 4.45) (McGuire and Howell, 1963; Fenstermaker, 1968). Porosity in the field is highly variable and associated with fractures. High pressures and low injection rates encountered while "fracking" wells (inducing fractures for increased permeability) suggest low permeabilities away from fractures in this field (Fenstermaker, 1968).

In the Thomas Ridge Pool of Casey County, several wells produce from an apparent paleotopographic high on the post-Knox unconformity surface at depths of 1,385 to 1,708 ft. The field has 40 ft of structural relief and is approximately 5,000 ft in diameter. The W.H. Pitts No. 3 Luttrell well was cored and had 13 ft of net pay with permeability greater than 0.1 md, average permeability of 3.2 md (range of 0.28 to 37 md), average porosity of 8.3 percent, and water saturation of 52.4 percent. Porosity was reported as intercrystalline and irregular. Vertical fractures were also noted in the core (McGuire and Howell, 1963).

In Bath County, the Judy and Young No. 1 Rose Run Iron Works well and Friestadt No. 1 Wright well both encountered gas and large amounts of salt water from zones 10 to 50 ft beneath the post-Knox unconformity at depths of more than 1,800 ft below the post-Knox unconformity.

In Carter County, the James Proctor No. 1 Burton well encountered gas and 1,000 ft of salt water at 3,551 to 3,575 ft, which is 218 ft from the top of the Beekmantown into the Rose Run Sandstone (McGuire and Howell, 1963).

These examples show that different potential porosity zones occur in the upper Knox, and that more work is needed to determine which are widespread. Gas shows have also been reported in Bell, Leslie, and Lewis Counties.

Western Kentucky Deep Porosity. In the Illinois Basin, few wells penetrate the upper Knox, but several wells indicate potential porosity. At least four wells in Meade, Hart, and Barren Counties have used the upper Knox for saltwater injection (Fig. 4.45). Depths to injection intervals range from 1,680 to 3,212 ft. Injection intervals are all openhole across hundreds of feet of Knox carbonates, rather than into individual, discrete porosity zones. These wells indicate that the Beekmantown is capable of accepting injected fluids, although information is currently lacking on the amounts of fluid injected and durations of the injections.

The IMCO Recycling Inc. well in Butler County (blue circle in Figure 4.43) has been operating as a nonhazardous Class 1 disposal well for brine and landfill runoff since 1995. The reservoir for waste disposal is the Knox Group (both the upper and possibly lower Knox). According to EPA records, injection of the brine is into a 1,754-ft-thick openhole interval between 4,690 and 6,450 ft depth, and includes the upper and part of the lower Knox. The density-porosity log shows numerous thin zones of porosity, some as high as 20 percent, separated by thicker nonporous zones (Fig. 4.48). Based on the UIC permit applications, the first test indicated the targeted injection interval would not accommodate the required volume of fluids that were planned to be disposed of from the plant. To increase injectivity, 27 zones (each 1 to 28 ft thick) were shot and treated with 15,000 gal of 28 percent HCl (acid) in five stages. The treatment worked, with injection rates changing from 14 gal/min with 1,000 psi wellhead pressure before treatment to 84 gal/min with 888 psi wellhead pressure after treatment. Actual rates of disposal range from 69,661 to 1,713,918 barrels/yr and pressures ranging from 520 to 1,220 psi. In 11 years, more than 3.5 million barrels of injectate have been disposed of in this Knox well, according to EPA records. There are no nearby wells, so the lateral extent of individual porosity zones is unknown. Nor is information available on which of the Knox zones are taking the fluids.

In westernmost Kentucky, porosity may also be associated with the Everton Formation, a dolomite just above the Beekmantown, which is not preserved farther east. Schwalb (1968) inferred that a lost circulation zone in the South Central Petroleum No. 1 Pearl well, Calloway County (top of Knox is at 2,690-ft depth), and a drillstem test recovery of salty, sulfurous water at the rate of 40 barrels per hour in Shell Oil No. 1 Davis well (top of Knox is at 4,735-ft depth) in Crittenden County from 300 to 700 ft below the St. Peter Sandstone may be an indication of porosity associated with the sub-Everton unconformity (Schwalb, 1968).

Hancock County CO_2 Injection Demonstration. The Kentucky Geological Survey No. 1 Marvin Blan well was drilled in Hancock County, Ky. (white square in Figures 4.43 and 4.44), in the summer of 2009 for the purpose of testing the Knox Group for carbon seques-

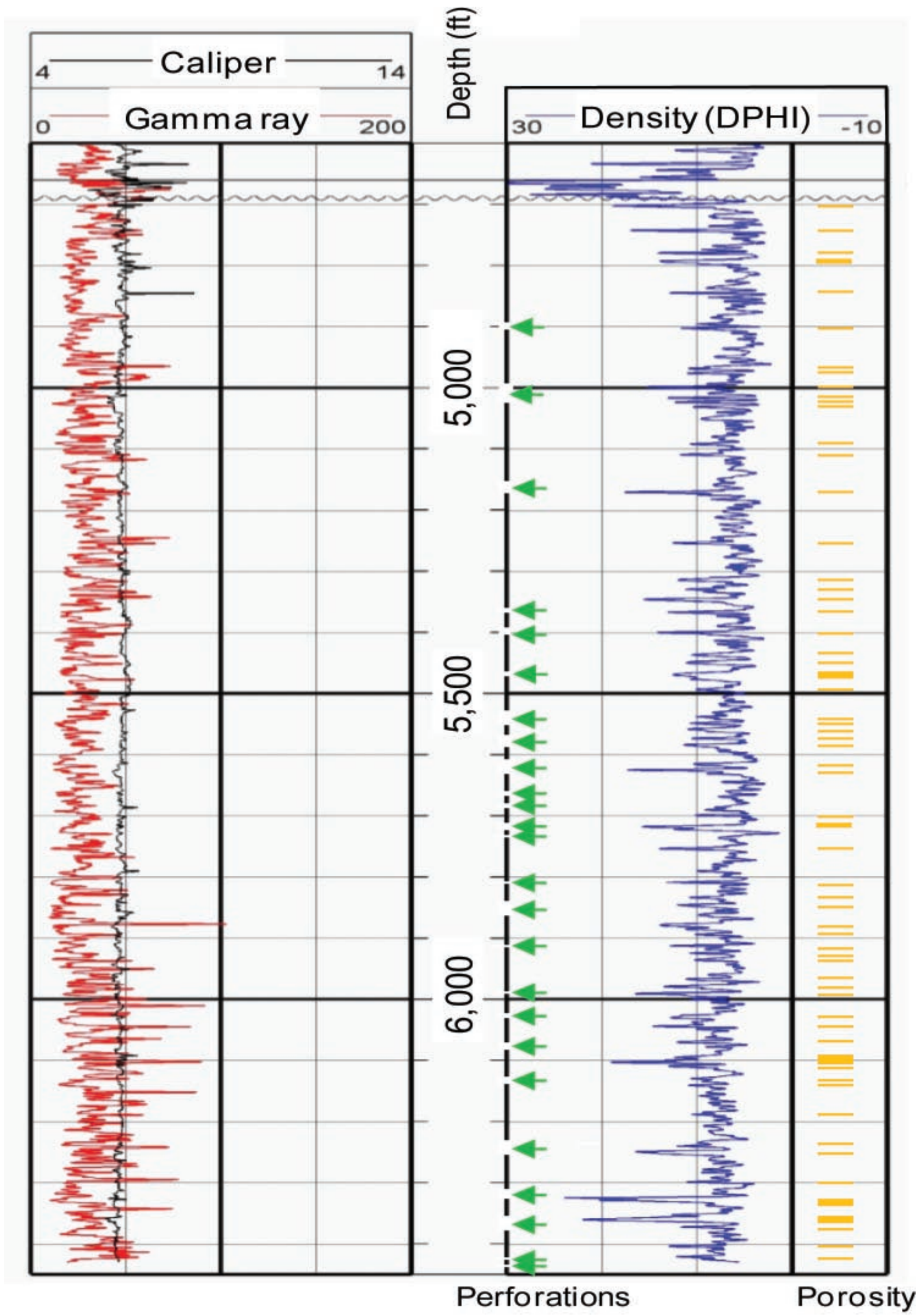

Figure 4.48. Geophysical log from the IMCO Recycling well in Butler County. The density log (DPHI) indicates numerous discrete, thin porosity zones (black arrows) in the Knox into which wastes are being injected. Note the thick intervals of nonporous dolomite between the discrete porosity zones. To enhance porosity, the well was shot (green arrows) and treated with acid. Well location shown by blue circle in Figure 4.43.

tration. The well was funded by the Kentucky Consortium for Carbon Storage with funding from Kentucky's House Bill 1 (August 2007), Peabody Energy, ConocoPhillips Company, E.ON U.S., Tennessee Valley Authority, Illinois Office of Coal Development, U.S. Department of Energy, National Energy Technology Laboratory, and others. The following information was provided by Rick Bowersox of the Kentucky Geological Survey.

The Beekmantown Dolomite was penetrated at 5,347 ft and was 1,567 ft thick. In core, dolomites consisted of fabric-preserving primary dolomite and fabric-destructive secondary dolomite, with vug-filling saddle dolomite, vug-lining chert, chert nodules and fracture fills, and nodular to disseminated pyrite. Average porosity calculated from the density log was 6.34 percent.

Openhole injection tests of brine below a single packer at the top of the Knox were able to inject 18,454 barrels of brine and borax solution into the upper Knox, Gunter Sandstone, and lower Knox, at rates of as much as 14 barrels/min, with wellhead pressures of 285 to 550 psi. Temperature logs showed that 70 percent of the injected brine went into the upper Knox and Gunter. Injection of a borax tracer solution and monitoring with pulsed neutron and spinner logs confirmed these results.

CO_2 injection began on August 19, 2009. A total of 323 short tons of CO_2 was injected openhole into the upper and lower Knox at the pumping equipment maximum rate of 4.1 barrels/min. This was the first demonstration of CO_2 injection into the Knox in the United States. Temperature logs were run after injection to verify CO_2 placement. The wellbore was then flushed with brine and temporarily abandoned with downhole pressure monitoring in place, pending additional testing to be completed in early 2010. Final results and a report will be posted at the Kentucky Consortium for Carbon Storage Web site.

Further testing in the Blan well will be funded as part of a U.S. Department of Energy grant from the American Recovery and Reinvestment Act to the University of Illinois, Illinois State Geological Survey, and its partners, including the Kentucky Geological Survey. More information on this well can be found at the Kentucky Consortium for Carbon Storage Web site (www.uky.edu/KGS/Kentucky Consortium for Carbon Storage/).

Overlying Sealing/Confining Units. In Knox reservoirs beneath the unconformity, the surrounding dense carbonates of the Knox and overlying Wells Creek Formation (where the St. Peter Sandstone is absent) provide adequate seals for the reservoir. Permeabilities in dense dolomites of the upper Knox are typically less than 0.01 md. Vertical hydraulic conductivities in the Knox-equivalent dolomites in the northern Midwest range from 8.6×10^{-7} to 1.1×10^{-3} ft/day (Young, 1992). In a regional model of the Knox as a confining unit, Mandle and Kontis (1992) inferred a vertical hydraulic conductivity of 1.0×10^{-11} ft/sec.

In several oil fields and existing gas storage fields, limestones and dolomites of the overlying Wells Creek Formation are the seal for upper Knox porosity zones. The Wells Creek is generally dense and argillaceous, which should make an adequate immediate seal, although fractures may occur in areas of abrupt thickness changes in the underlying Knox unconformity surface. The Wells Creek is overlain by mostly dense carbonates of the Trenton–Black River Groups (Middle Ordovician carbonate interval), which offer good secondary seals. Above that (off of the Cincinnati Arch) are the regional confining shales of the Upper Ordovician shales (Maquoketa and its equivalents). In the basins, the Devonian shales are also shallower confining intervals (Figs. 4.4–4.5).

Few wells have been drilled into the upper Knox in western Kentucky, so there should be no sealing issues related to old wellbores. More wells penetrate the upper Knox in eastern Kentucky, but the density is still low. Only in south-central Kentucky where there has been significant oil production would the number of wells and wellbore integrity likely be an issue, and in these areas the upper Knox is very shallow and unlikely to be used as a carbon storage reservoir.

CO_2 Storage Potential. The top of the upper Knox is less than 2,500 ft deep in the central third of Kentucky, so it would not be considered for large-volume carbon storage in those areas. A quantitative assessment of the storage capacity of the upper Knox to the east and west has yet to be undertaken, mostly because it is a thick, heterogeneous carbonate reservoir and calculations used for regional sandstone aquifers would likely not apply to more complex carbonate reservoirs. Work is ongoing at the Kentucky Geological Survey, Kentucky Consortium for Carbon Storage, and regional DOE partnerships to further investigate this unit's potential. The success of two gas storage fields and several saltwater injection projects at shallower depths, and common encounters with saline brines in wells drilled into the upper Knox in Kentucky, provide optimism for this unit's storage potential at greater depths, although more research is needed before large-scale sequestration can be realized. If even a small percentage of the total volume of the upper Knox in eastern and western Kentucky has porosity, the potential storage volumes for this unit are high.

Gravity analyses in northern Kentucky (Cincinnati area) indicate that structural highs on the upper surface of the Trenton Limestone were associated with highs on the underlying Knox unconformity surface (Schmidt and Warner, 1964). It might be possible to use shallower Trenton structures to aid in predicting paleotopographic highs on the Knox unconformity surface for carbon storage using gravity or seismic analysis. Typical oil fields developed in paleotopographic highs on the Knox unconformity surface at shallower depths are small in area, so many such fields would be needed for a large-volume carbon storage project. Openhole completions of thick Knox sections may also be needed in a large-volume storage project in order to intersect several discrete porosity (vugular or fracture) zones in the Knox (if such completions are allowed by the EPA when rules for carbon storage are finalized). An openhole completion was used in the CO_2 demonstration test in the Kentucky Geological Survey No. 1 Marvin Blan well, Hancock Co., Ky. Openhole completions would complicate monitoring of the subsequent plumes of injected carbon dioxide. Also, in Kentucky's two Knox waste-injection projects (discussed in the lower Knox–Copper Ridge section), stimulation was needed to improve injectivity. Stimulation was not used in the Hancock County test well because it was not needed for the scale of demonstration. Stimulation would likely be needed in a large-volume storage project in the upper Knox.

St. Peter Sandstone

CO_2 unit type: possible regional/local reservoirs
KGS stratigraphic code: 365STPR
Series/system: Ordovician
Thickness: 0–159 ft
Distribution: western (north), central (north), and eastern Kentucky
Number of wells with completion: 49
Number of wells that TD: 48
Approximate number of wells drilled through unit: 11,492

Interval Definition. The St. Peter Sandstone is the first sandstone above the post-Knox unconformity. It overlies the Beekmantown Dolomite across most of the state and the Everton Dolomite in far western Kentucky (Figs. 4.4–4.5). The sandstone is capped and laterally interfingers with carbonates of the Wells Creek Formation (Fig. 4.4). In western Kentucky (at least), the interval discussed in this report is the same as the formal formation. In Kentucky, the St. Peter Sandstone is not continuous across the Cincinnati Arch, and there has been some debate as to whether or not a sandstone in eastern Kentucky similar to the St. Peter is equivalent to the formal St. Peter of the Illinois Basin and western Kentucky. Also, a local Knox stray sand may occur in the upper Knox, which can be confused with the St. Peter Sandstone. The source of the St. Peter in eastern Kentucky may have been from erosion of the Rose Run Sandstone beneath the post-Knox unconformity (Price, 1981). For the purposes of carbon storage, however, the sandstone is in a similar stratigraphic position (above the post-Knox unconformity) in both basins, and is treated as the same unit.

General Description. The St. Peter Sandstone is one of the regional saline aquifers being studied by the Midwest Regional Carbon Sequestration Partnership and Midwest Geological Sequestration Consortium (Frailey and others, 2005; Wickstrom and others, 2005). The sandstone is a very fine- to medium-grained quartzarenite with subrounded to rounded, frosted grains. Cements in the St. Peter are dominated by calcite and dolomite in Kentucky, although chert, chalcedony, anhydrite, and minor chlorite are known in other parts of the Illinois Basin (Hoholick and others, 1984). In western Kentucky, sample descriptions for the St. Peter were obtained from the Texas Gas Transmission No. 1 Shain well, Grayson County. These descriptions can be accessed online at the Kentucky Geological Survey's Oil and Gas Database. Descriptions of samples from eight wells in eastern Kentucky are provided in McGuire and Howell (1963).

The St. Peter reaches thicknesses in excess of 1,000 ft in Michigan, and is hundreds of feet thick across much of the northern Illinois Basin, which is why it is one of the units being concentrated on in the Midwest for possible carbon storage. It thins dramatically to the south, however, either pinching out or grading into carbonate rocks in several parts of Kentucky. In western Kentucky, the sandstone appears to thicken to the west, reaching 80 ft along the Rough Creek Fault System and along the Mississippi River (Fig. 4.49), although thickness data are scarce and estimates are based mostly on seismic analysis and data from southern Illinois. In some areas, the thickness of the sandstone interval shown in Figure 4.49 includes sandy carbonates interbedded with sandstones.

The southern edge of the sandstone is poorly defined, which is why the zero line is dashed in Figure 4.49. South of the Rough Creek Fault System, for

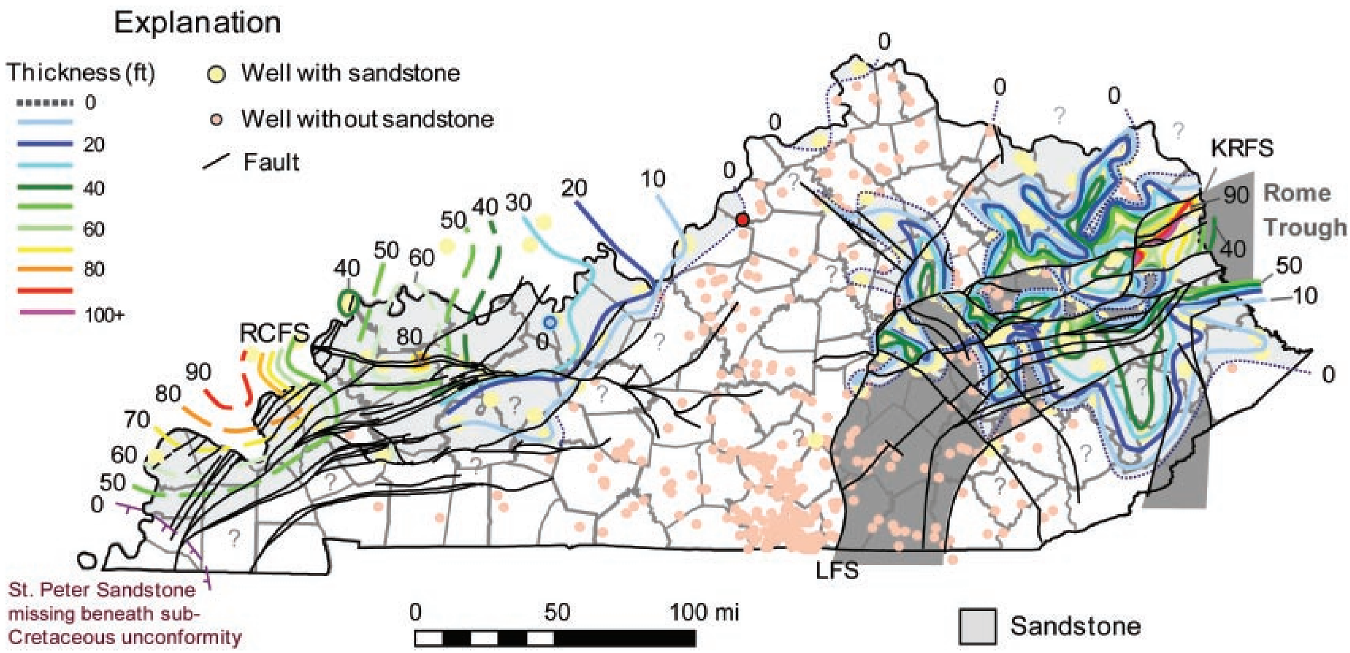

Figure 4.49. Thickness of the St. Peter Sandstone in Kentucky. The extent of the interval is shown in light gray. Areas in white lack distinctive sandstone, although there may be sandy carbonates at the St. Peter horizon. The thickness shown here is the thickness of the entire interval and does not indicate porosity or potential reservoir thickness. Only a small part of this thickness and extent might be available for carbon storage. The Rome Trough is shaded in dark gray. In eastern Kentucky, where dark gray areas appear through the light gray shading, the St. Peter is absent. The Rough Creek Graben is not shaded in this diagram. The Ballardsville Field in Oldham County (red circle) has a sandstone that may be the St. Peter Sandstone or a Knox sand. KRFS = Kentucky River Fault System. LFS = Lexington Fault System. RCFS = Rough Creek Fault System.

example, the few wells that have been drilled through the St. Peter show that sandstone interfingers with carbonates or grades into sandy carbonates. The actual interval in which sandstones are interbedded with carbonates or sandy carbonates may be 20 to 40 ft thick, but the thickness of individual sandstones is usually less than 15 ft thick. Differentiating sandstone from sandy carbonates is difficult in many of the wells. In addition, in Bullitt, Hardin, Jefferson, Nelson, and Oldham Counties, along the thinning edge of mapped St. Peter Sandstone, a sandstone has locally been mapped as an upper Knox sandstone because it is overlain by thin dolomites. If these dolomites are part of the overlying Wells Creek Formation rather than the Knox, this sand is equivalent to the St. Peter Sandstone. Part of the gas storage in the Ballardsville Field of Oldham County (red circle in Figure 4.49) may have been in this sandstone. Similar sands were noted on drillers' logs from several counties southwest of the Ballardsville Field; however, where samples were described from these wells, most appear to be sandy zones in the upper Knox rather than distinct sandstones in the Knox or St. Peter. More research is needed to better understand and differentiate these upper Knox sandy zones from thinning St. Peter Sandstone.

In Kentucky, the St. Peter of the Illinois Basin (western Kentucky) appears to be separated from the St. Peter of the Appalachian Basin (eastern Kentucky) across the Cincinnati Arch. In general, the St. Peter in western Kentucky has a more blanket-like distribution, whereas in eastern Kentucky it has a highly irregular distribution (Fig. 4.49). In eastern Kentucky, the sandstone is centered in the Rome Trough and then branches out to the north and west. Many of the elongate extensions in the St. Peter distribution shown in Figure 4.49 represent attempts to correlate isolated data outside of the Rome Trough, and the actual distribution may be even more complicated than shown. There may be a possible narrow connection between the basins in Henry County where a well drilled on the downthrown side of a northwest–southeast-oriented basement fault encountered 10 ft of outlying St. Peter Sandstone.

Faults significantly influence St. Peter thickness within the Rome Trough. Some fault blocks in Elliott and Lawrence Counties have more than 130 ft of sandstone, whereas other fault blocks have no St. Peter

Sandstone (Fig. 4.49). Abrupt variations in thickness across faults of the Kentucky River Fault System on the northern margin of the Rome Trough indicate significant structural control (mostly growth faulting) on sand distribution (Price, 1981; Sutton, 1981). Thickness is also influenced by paleotopographic lows on the post-Knox unconformity surface (Sutton, 1981). Differentiating the two influences without close well-spacing would be difficult.

The St. Peter does not crop out at the surface in Kentucky, and is shallowest in Scott, Woodford, and Fayette Counties (Fig. 4.50). This area corresponds to a structural high on the Cincinnati Arch, termed the Lexington or Jessamine Dome. The sandstone is less than 2,500 ft deep across the central third of the state. Eastward, the St. Peter gradually deepens to more than 9,300 ft (7,500 ft below sea level) in easternmost Pike County. Westward, the sandstone deepens to more than 8,250 ft below sea level south of the Rough Creek Fault System in Union County, western Kentucky (red line near RCFS in Figure 4.50).

Known Reservoirs or Types of Porosity. Regionally, the St. Peter is thickest in the Illinois and Michigan Basins, and thins south and east toward the Appalachian Basin. Few wells have been drilled to the St. Peter in western Kentucky. Those that do are mostly north of the Rough Creek Fault System or on the eastern margin of the Illinois Basin. In most of the wells, the St. Peter has little porosity. At shallower depths (1,200 to 1,700 ft) between Hardin and Oldham Counties, a sandstone occurs near the top of the Knox, which may be the St. Peter or a sandy zone in the upper Knox (see previous section). Water is commonly encountered in this interval, but the St. Peter is too shallow for carbon storage in this area.

In Kentucky, the St. Peter Sandstone is thickest in isolated fault blocks of eastern Kentucky (Fig. 4.49), in the Appalachian Basin portion of the state. Likewise,

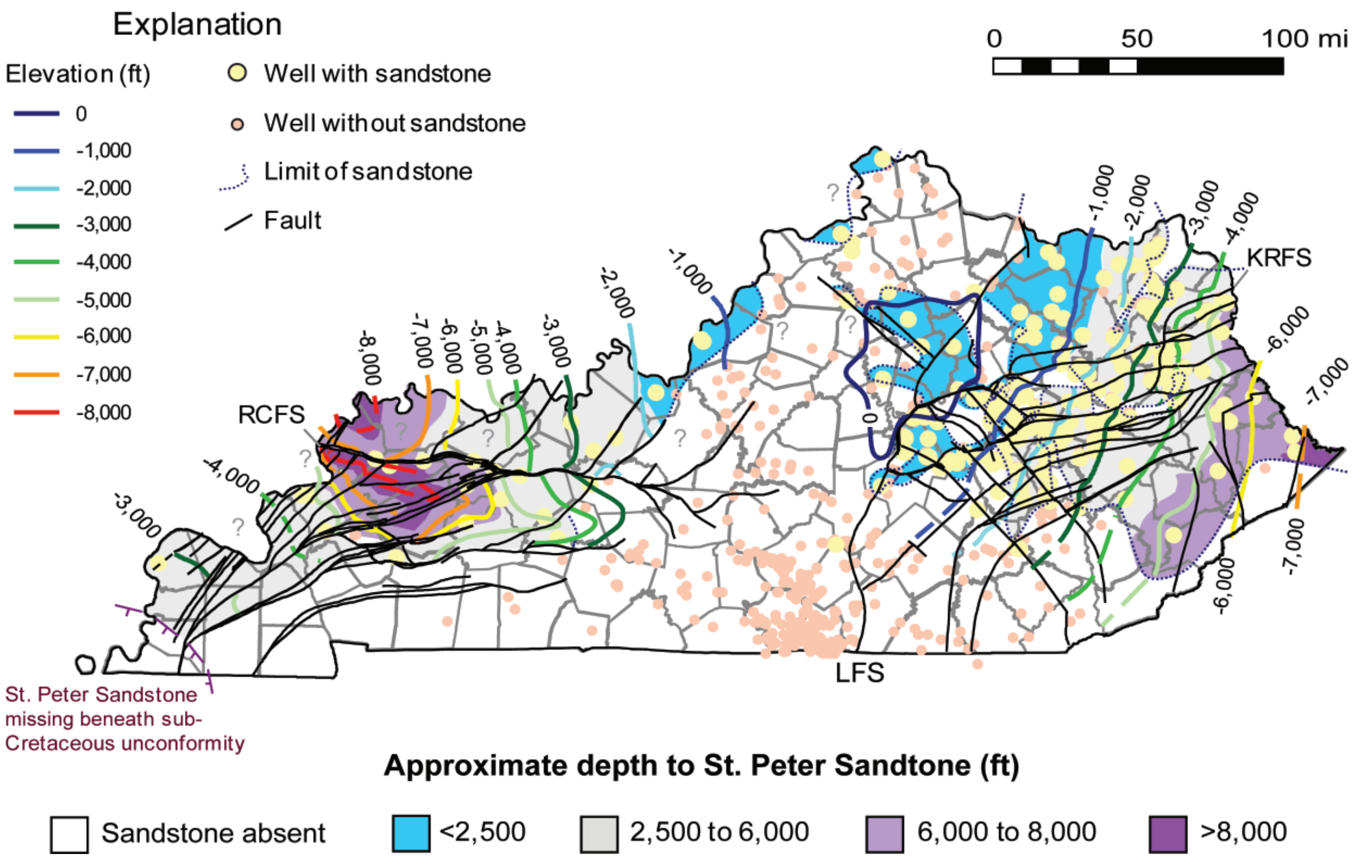

Figure 4.50. Structural elevation on top of the St. Peter Sandstone. Areas less than 2,500 ft deep are shaded blue, and areas more than 6,000 to 8,000 ft in depth are shaded in two shades of purple. Structural elevation lines are extended beyond the actual extent of the sandstone into lateral sandy carbonates or the top of the Knox. KRFS = Kentucky River Fault System. LFS = Lexington Fault System. RCFS = Rough Creek Fault System. Elevations in western Kentucky are mostly based on seismic interpretations.

Kentucky oil and gas production from the unit is restricted to eastern Kentucky (Fig. 4.51), and in general, the sands in parts of eastern Kentucky have better porosity than those in western Kentucky. Twenty-four wells have reported completions in the St. Peter in eastern Kentucky and are more than 2,500 ft deep (Table 4.4).

Most deep completions are in the Furnace Field of Estill and Powell Counties (Fig. 4.51, Table 4.4). This field produced from 35 to 65 ft of St. Peter Sandstone at depths of 2,520 to 2,650 ft. The field had total production of 1.8 billion ft^3 of subcommercial gas before depletion. The gas was subcommercial because it contained 25 to 40 percent CO_2 (naturally). The gas was used to repressure the Lockport Dolomite (Corniferous) in the Big Sinking oil field (Price, 1981). McGuire and Howell (1963) summarized gas analyses and production from the field.

Homer (Isonville Consolidated) Field. The deepest St. Peter completions to date are in the Stephens and Homer Fields of Elliott County (Fig. 4.51, Table 4.4). Both fields are developed along faults on the northern margin of the Rome Trough. Three wells produce from the St. Peter in the Homer Field, Elliott County (Fig. 4.51) (Hickman and Harris, 2004). The thickness of the sandstone varies greatly across faults, from 23 ft in the Carson Associates No. 57 Prichard Heirs well to 150 ft thick in the Carson Associates No. 1 Kayzee well (Fig. 4.52). The sandstone is trapped downdip of the Isonville Fault and is juxtaposed against the Beekmantown Dolomite (upper Knox) at depths of 4,120 to 4,293 ft (Hickman and Harris, 2004). Porosities calculated from logs average 6 percent, but are as high as 20 percent.

Trapp Field. The Trapp Field of Clark County (Fig. 4.51) produces from 40 to 50 ft of St. Peter Sandstone at an average depth of 1,700 ft. Average porosity is 12 percent. The field is developed on a semicircular structural closure of 30 to 50 ft (Fig. 4.53). The shape of the structure may indicate some control from the

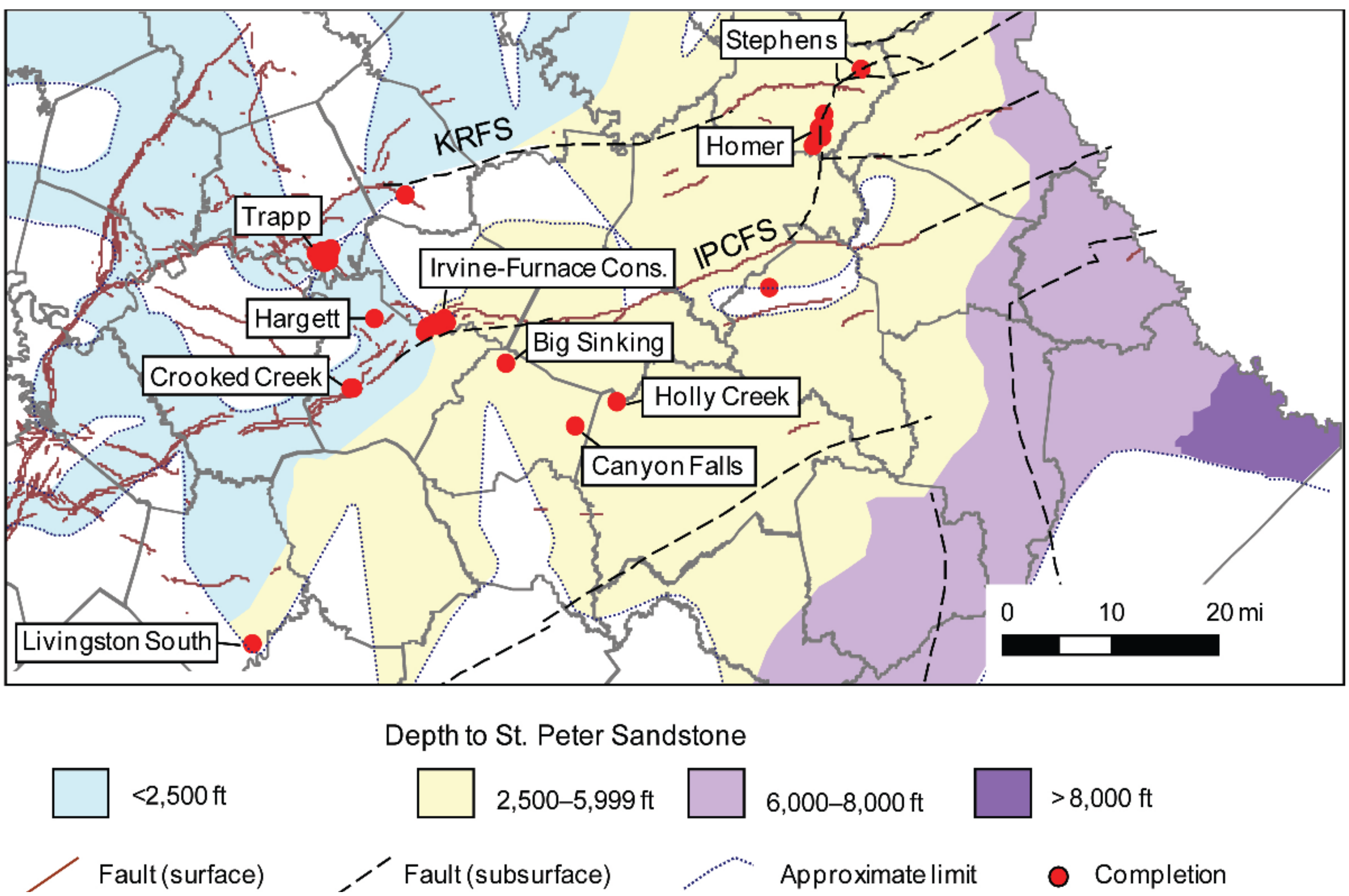

Figure 4.51. Reported completions in the St. Peter Sandstone in Kentucky. IPCFS = Irvine–Paint Creek Fault System. KRFS = Kentucky River Fault System.

Table 4.4. St. Peter Sandstone completions in Kentucky reported deeper than 2,500 ft, arranged by depth. See Figure 4.51 for locations. Geophysical logs and well records for these completions can be viewed online at the KGS Oil and Gas Database.

No. of Wells with Completions	*Depth (ft)*	*Example KGS Record Nos.*	*Field*	*County*
1	4,634–4,646	8424	Stephens	Elliott
6	4,068–4,500	114444, 116061, 126651	Homer (Isonville Cons.)	Elliott
1	3,787–3,797	18425	Holly Creek	Breathitt
1	3,717–3,797	71237	Canyon Falls	Lee
1	2,950–3,131	121910	Big Sinking	Lee
1	2,570–2,635	16624	Livingston South	Rockcastle
13	2,520–2,650	16454, 16456, 8621	Furnace	Estill, Powell

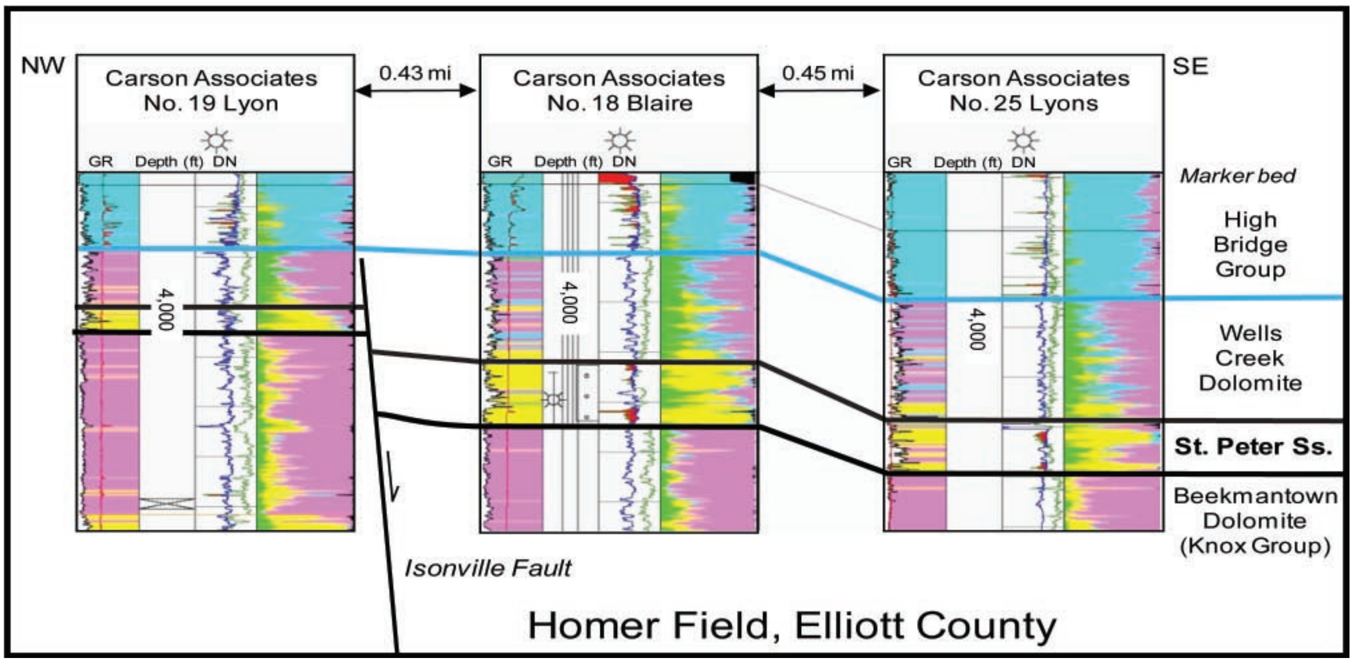

Figure 4.52. Thickness changes in the St. Peter Sandstone across the Isonville Fault in the Homer Field, Elliott County. Modified from Hickman and Harris (2004). In the logs, colors for gamma (left side) and density-neutron (right side) are shaded to represent more limestone-dominated (blue), dolomite-dominated (pink), shale-dominated (green), and sandstone-dominated (yellow) zones. See Figure 4.51 for location.

underlying unconformity surface on top of the Knox. McGuire and Howell (1963) noted that the sandstone thins and becomes less permeable away from the small field. All of the productive wells were hydraulically fractured. Approximately 411 bcf of subcommercial gas was produced prior to saltwater encroachment (Price, 1981).

Depth Relationships. Hoholick and others (1984) noted a depth-porosity relationship for the St. Peter Sandstone in the Illinois Basin similar to, but slightly different from, the Mount Simon Sandstone (Fig. 4.54). In the St. Peter, porosity declines relatively rapidly at depths of less than 4,000 ft from 30 to 10 percent, and more gradually declines at greater depths. Porosities of less than 5 percent were generally reached at more than 6,000 ft. Secondary porosity, where developed, is likely from dissolution of quartz and cements, and fractures. Hoholick and others (1984) found that fracture porosity is important at depths of more than 6,000 ft in the Illinois Basin, although most of the deep wells used in the study were drilled on structure in hopes of finding structural traps. Fractures would be relatively more common near structures than away from structures. Whether or not the same relationship

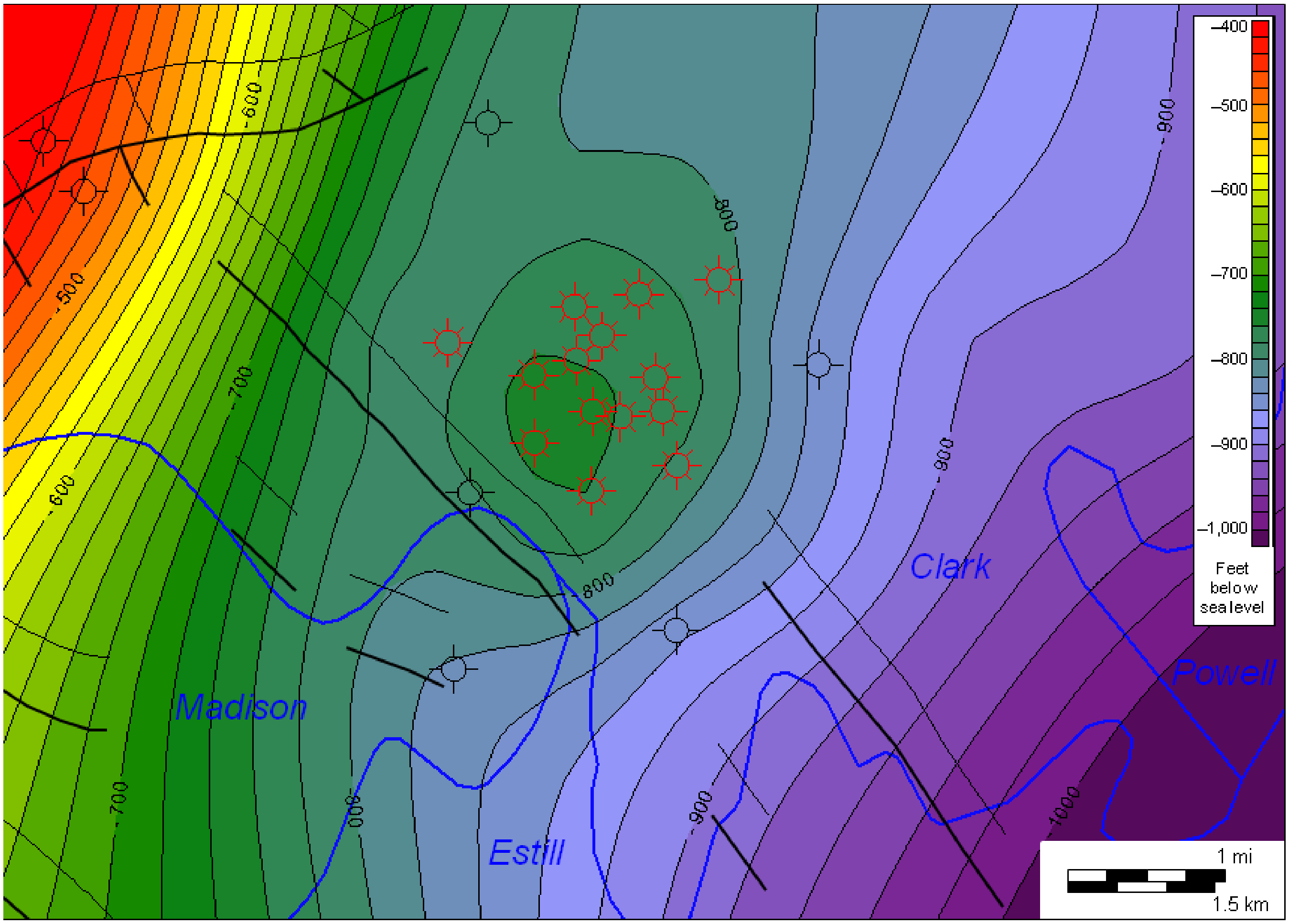

Figure 4.53. Structural elevation on top of the St. Peter Sandstone in the Trapp Field, Clark County, showing structural closure in the field. Datum is sea level. Contour interval is 20 ft. Map courtesy of Dave Harris. See Figure 4.51 for location.

holds for the St. Peter in the Appalachian Basin is uncertain. Known completions, however, are at depths of less than 6,000 ft (Table 4.4). Depths of more than 6,000 to 8,000 ft are highlighted in the structure map (Fig. 4.50) for both basins to show where the sand may be too deep for optimal porosity.

Overlying Sealing/Confining Units. The overlying Middle to Upper Ordovician carbonate interval (Wells Creek Dolomite and Trenton–Black River carbonates) is the immediate confining unit. Details of this interval are discussed in the next section. Off of the Cincinnati Arch, the Upper Ordovician shales (Maquoketa, Clays Ferry, Kope) and the Devonian shale would be additional seals (Figs. 4.4–4.5). Few wells are drilled to the depths of the St. Peter in western Kentucky, so there should be no sealing issues related to old wellbores. More wells are drilled into the St. Peter in eastern Kentucky, but the density is still low.

CO_2 Storage Potential. The St. Peter is less than 2,500 ft deep in the central third of the state, so it would not be considered for large-volume carbon storage in those areas. Likewise, it is more than 6,000 ft deep in easternmost Kentucky, far western Kentucky, and parts of the Rough Creek Graben, which would also limit its use for large-volume storage because of the possible loss of porosity with depth (Hoholick and others, 1984). Schwalb (1969) noted that the sandstone may be flushed with fresh water downdip from its truncation by the sub-Cretaceous unconformity in the Mississippi Embayment area, which would influence its ability to be used for carbon storage under underground injection control regulations in far western Kentucky.

The St. Peter's storage capacity in western Kentucky was calculated as 0.7 billion short ton (0.6 billion metric ton) at 4 percent storage volume, and 0.1 billion short ton (0.1 billion metric ton) at 1 percent storage volume in the Midwest Geological Sequestration

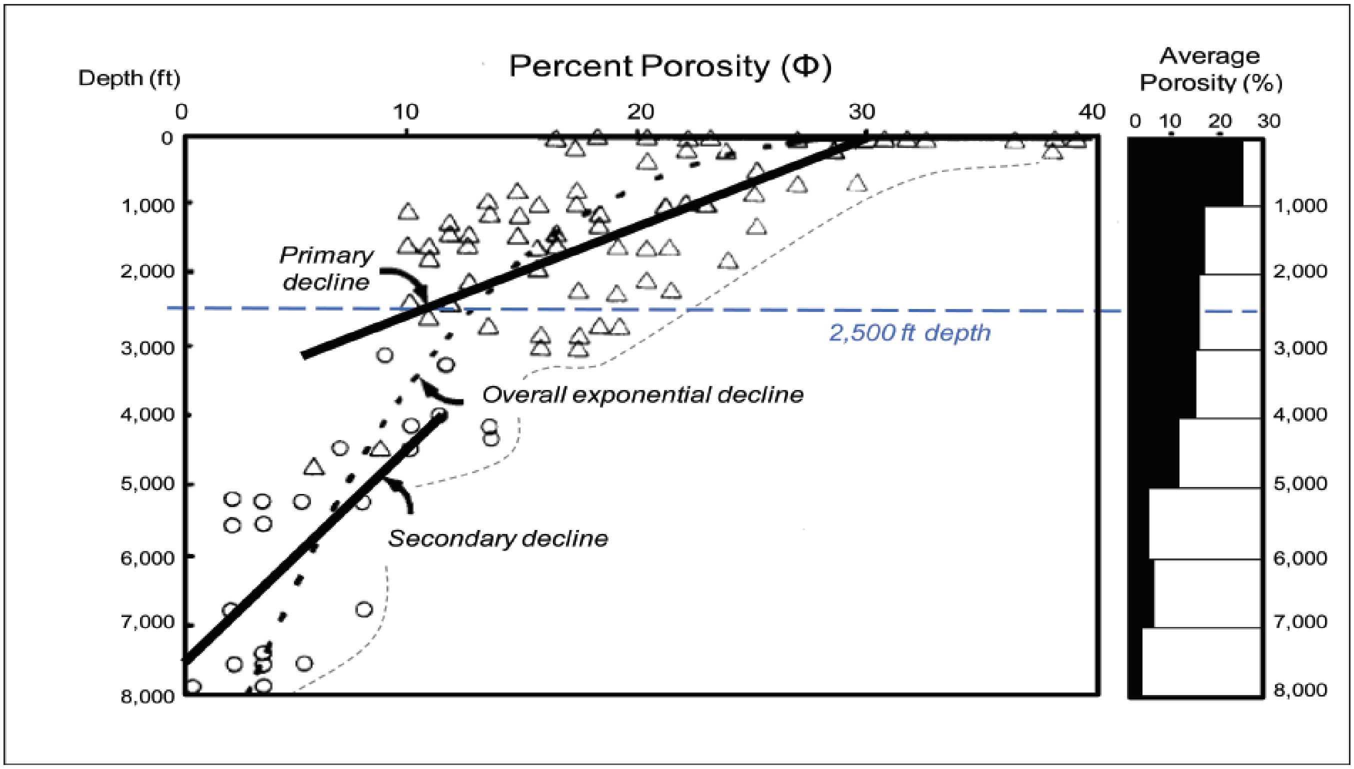

Figure 4.54. Porosity versus depth relationship for 144 samples of the St. Peter Sandstone in the Illinois Basin. Triangles = primary porosity. Circles = secondary porosity. Modified from Hoholick and others (1984); AAPG © 1984, reprinted by permission of the AAPG whose permission is required for further use.

Consortium's phase I report (Frailey and others, 2005). The storage volume was not calculated for eastern Kentucky in the phase I report of the Midwest Regional Carbon Sequestration Partnership (Wickstrom and others, 2005), but known production and porosity indicates that it has potential in parts of eastern Kentucky for small- to possibly large-scale storage. Some of the difficulties with calculating realistic storage capacities for the sandstone in eastern Kentucky are the extreme lateral variations in thickness as well as known variability in porosity. All existing fields and completions are in structural or stratigraphic traps of small area, which would likely be insufficient for large-scale carbon storage. Water has been encountered in some St. Peter sands in northeastern Kentucky that were not in obvious structural traps, so there is the possibility of larger, nonstructurally confined porosity areas. Because the sandstone overlies the Knox, there is also the possibility of stacked stratigraphic intervals in which thinner or more aerially restricted St. Peter reservoirs might be used in combination with other horizons to achieve large-volume storage.

One consideration for using the St. Peter Sandstone as a storage reservoir in eastern Kentucky, south of the Kentucky River Fault System (in the Rome Trough), would be that the thickest and most porous sandstones tend to be associated with faulting, which might require proving that faults were sealing rather than transmissive prior to injection.

In eastern Kentucky, another consideration is that several wells have encountered natural CO_2 in the St. Peter Sandstone. On the positive side, these fields demonstrate that the sandstone is capable of holding CO_2. If injection is planned in the St. Peter, gas should be sampled and analyzed to determine an isotopic signature for any natural CO_2 so that it could be differentiated from injected CO_2 during subsequent monitoring of the storage field.

Because the St. Peter Sandstone tends to have a carbonate cement in Kentucky, porosity and injectivity near the wellbore might be increased with acid treatments, although more analysis would be needed. Fracturing and other treatment options might also be needed. In both basins, if porosity is encountered in a thin St. Peter interval, the possibility of openhole completions with the underlying Knox Group might be considered to take advantage of any porosity that might be available in the underlying Knox.

Middle-Upper Ordovician Carbonates

CO_2 unit type: possible local reservoirs and secondary confining unit
KGS stratigraphic code: 365KMCK, 365LXTN, 365TRNT, 365HGBG, 365STRV, 365WLCK
Series/system: Ordovician
Thickness: 650–1,500 ft
Distribution: statewide (crops out in central Kentucky)
Number of wells with completion: 2,305
Number of wells that TD: 4,569
Approximate number of wells drilled through unit: 11,540

Interval Definition. The Middle-Upper Ordovician carbonate interval includes all strata above the St. Peter Sandstone, or where the sandstone is missing, above the post-Knox unconformity, to the base of the Upper Ordovician shale interval (Maquoketa Formation and equivalent units). This interval includes the Wells Creek, Joachim, Dutchtown, High Bridge (Black River), Lexington (Trenton), and Kimmswick Formations (Figs. 4.4–4.5). Stratigraphic nomenclature from surrounding states is commonly used by drillers in this interval, including Stones River (for High Bridge through Wells Creek interval) and Murfreesboro (for Camp Nelson Limestone of the High Bridge Group) from Tennessee. The term "Trenton" is also commonly used for the Lexington Limestone by drillers. The formal base of the Upper Ordovician in Kentucky was initially defined to be the top of the Lexington Limestone, but recently the International Commission on Stratigraphy (2004) adjusted the global definition of that boundary, and now the boundary would be the base of the Blackriveran Stage (Gradstein and others, 2004), which is the base of the High Bridge Group in Kentucky. The Wells Creek, Dutchtown, and Everton Formations are part of the Middle Ordovician (Figs. 4.4–4.5). For the purposes of this report, the Everton Formation of western Kentucky was included with the upper Knox interval because of its position beneath the St. Peter Sandstone.

General Description. The base of the interval is the base of the Wells Creek Formation. This unit consists of limestones, dolomites, pyritic green shales, and minor dark shales. Carbonates may intertongue with siltstones and sandstones of the St. Peter Sandstone. Where the St. Peter is missing, dolomites in the Wells Creek can rest directly on the Knox Group, which can complicate picking the top of the Knox in some areas. In south-central Kentucky, the Wells Creek is locally restricted to paleotopographic lows on the Knox unconformity surface (Norris, 1981). Sample descriptions from four wells in eastern Kentucky are provided in McGuire and Howell (1963). Additional descriptions can be found in Freeman (1951).

The middle part of this interval in Kentucky is the oldest rocks exposed at the surface in Kentucky. In central Kentucky they are called the High Bridge Group. The High Bridge consists of the Tyrone, Oregon, and Camp Nelson Formations (Cressman and Noger, 1976). The Tyrone has two bentonite layers (drillers' Mud Cave and Pencil Cave), which are important stratigraphic markers in the subsurface. In some wells, only one of the two layers may be recognized, which can lead to local miscorrelations of the top of the Tyrone Formation. Sample descriptions from 10 wells in eastern Kentucky are provided in McGuire and Howell (1963). Additional descriptions can be found in Freeman (1951). Individual formations of the group are rarely subdivided on subsurface oil and gas logs. The interval is also commonly called Stones River or Murfreesboro (Tennessee terminology) by drillers in southeastern Kentucky.

The upper part of the interval is equivalent to the Trenton stage of the Ordovician. Where these rocks crop out in central Kentucky they are called the Lexington Limestone. The Lexington is a complex mosaic of light brown to dark gray, bioclastic to argillaceous limestones and interbedded shales (Cressman, 1973). The Lexington Limestone is thickest in the Bluegrass Region on the Jessamine/Lexington Dome, and is mostly absent in western Kentucky. Where it is absent, the overlying Upper Ordovician shale interval (Maquoketa Formation and any overlying Ordovician strata) thickens.

Isopach and structure maps were not completed for this interval for this project. The total interval thickness from the top of the St. Peter Sandstone to the top of the Trenton limestone in eastern Kentucky is 1,100 to 1,500 ft thick. In western Kentucky, the Trenton part of the interval (upper part) thins from the crest of the Cincinnati Arch west to a feature called the Sebree Trough where the Trenton is thin or absent and the overlying Maquoketa Shale is thick (Schwalb, 1980; Kolata and Graese, 1983). The Trenton is missing in a broad belt that extends from Hancock and Daviess County on the northeast to Logan through Calloway Counties to the southeast (Kolata and others, 2001). West of the trough, the Trenton thickens again. The combined Trenton–High Bridge/Black River–Wells Creek carbonates east of the Sebree Trough are 650 to 800 ft thick. Within the Sebree Trough, the interval is generally around 650 ft thick. West of the trough the interval thickens to more than 1,200 ft in the Jackson Purchase Region, mostly because of thickening in the High Bridge/Black River part of the section (Kolata and others, 2001).

Known Reservoirs or Types of Porosity. The DOE-sponsored Midwest Regional Carbon Sequestration Partnership and Midwest Geological Sequestration Consortium's phase I studies treated this interval as a confining unit capped by the Upper Ordovician Maquoketa and equivalent shales (Frailey and others, 2005; Wickstrom and others, 2005). The thick section of limestones and dolomites, as well as interbedded shales, should make for an adequate seal in many parts of the state.

Although much of this interval is dominated by impermeable carbonates, there are numerous completions in the Middle-Upper Ordovician carbonate interval (Fig. 4.55). Most of the known completions in this interval are in fractured reservoirs in south-central Kentucky along the crest of the Cincinnati Arch (Clinton County near the Tennessee border) at depths of less than 2,500 ft. Many of these fields also have completions in underlying Knox carbonates (see Figure 4.46). Depths of more than 2,500 ft are limited to the approximate area of the Eastern and Western Kentucky Coal Fields. Most of the deep wells with oil and gas completions (Table 4.5) are associated with the faults (Fig. 4.55), suggesting that fracture porosity or secondary porosity associated with fluids along faults is important for porosity development in this interval at depth. Also, most of the deep oil and gas completions listed in Table 4.5 are in single wells. The lack of multiple wells in these locations suggests a lack of interconnected porosity intervals in many of the fields shown (especially away from faults).

The deepest completion in the Middle-Upper Ordovician carbonate interval is in western Kentucky, which is one of the few completions in this interval in the western part of the state. The Powell No. 1 Powell well (permit no. 17243), Sebree Springs Field, Webster County (Fig. 4.55, Table 4.5), reported a completion (but not production) in the Trenton limestone at depths of 4,811 to 4,826 ft. The well was drilled in 1948 and plugged in 1974. The field is a small, elongate pool oriented subparallel to faulting.

Burning Springs Consolidated. Most of the completions reported from the Middle-Upper Ordovician carbonate interval at depths of more than 2,500 ft are from the Burning Springs Consolidated Field of Clay County (Fig. 4.55, Table 4.5), so this field is representative of the best porosity that could likely be found in this interval at depth (under similar geologic conditions). The field is located along the Rockcastle Uplift, along the southern margin of the Rome Trough. Porosity in the field is highly variable, and associated with fractures. Completions in the field have been reported throughout the Middle-Upper Ordovician carbonate interval, and production is also reported from fractured carbonates in the deeper Knox Formation (Fenstermaker, 1968). Wickstrom (1996) summarized salient characteristics of the Trenton (Lexington Limestone) in the field. In 1996, commercial gas was produced from eight wells in fractured dolomites. The average depth to the Trenton (Lexington) portion of the reservoir is 2,000 ft (although completions in other parts of the Middle-Upper Ordovician carbonate interval are reported to depths of 3,905 ft) across an area of approximately 1,750 acres. The average pay thickness is 20 ft. Average log-based porosity is 9 percent (range of 4 to 20 percent). The field is estimated to have reserves of 2 million mcf.

Possibility of Hydrothermal Dolomites. Dolomites in the High Bridge Group are sometimes localized or thickened along faults in central Kentucky. This appears to have been caused by hydrothermal fluid movement along faults (Wilcox and others, 2002). There is interest in exploiting fault-controlled dolomitization as the result of significant natural gas discoveries in the Ordovician Trenton and Black River Formations in central New York and West Virginia. Whether or not porosity is associated with hydrothermal dolomitization in deeper parts of this interval in eastern and western Kentucky requires further research.

Overlying Sealing/Confining Units. For most of the completions in this interval, the surrounding and overlying carbonates form the immediate seal. The dense carbonate and interbedded shale section between the St. Peter Sandstone and Maquoketa Shale (Galena and Platteville Formations) has been included as part of the Maquoketa confining unit in several hydrologic studies (see references in Young [1992]). Vertical hydraulic

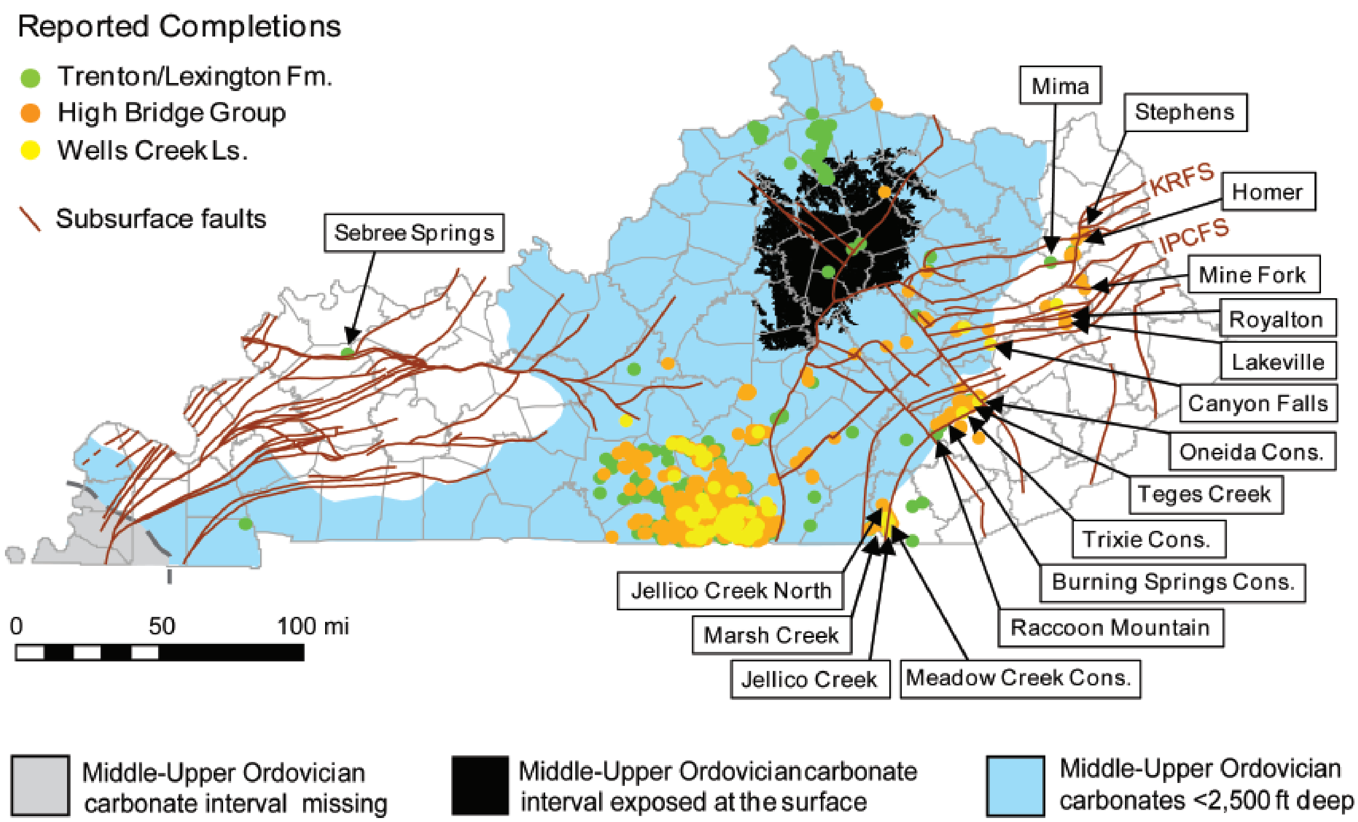

Figure 4.55. Kentucky wells with reported completions in the Middle–Upper Ordovician carbonate interval. There are a large number of completions in the shallow oil fields of south-central Kentucky. KRFS = Kentucky River Fault System. IPCFS = Irvine–Paint Creek Fault System. RU = Rockcastle Uplift. See Table 4.5 for more information on completions at depths of more than 2,500 ft. Field names in boxes are discussed in the text or shown in Table 4.5.

conductivities in these High Bridge–equivalent carbonates in the northern Midwest range from 3.0 x 10^{-3} to 7.0 x 10^{-5} ft/day (Mandle and Kontis, 1992).

Known fields with reported completions are mostly situated along faults or basement structures, and associated with fracture porosity. The fact that some fields along structures on the southern margin of the Rome Trough include fractured porosity through this unit and into the underlying Knox may suggest that they would not be an effective seal in parts of these areas, and the overlying Upper Ordovician shale interval would have to be considered the primary confining interval. The Upper Ordovician Maquoketa Shale (in the basins) is a regional confining interval.

CO_2 Storage Potential. The Middle-Upper Ordovician carbonate interval is a seal or confining interval. Dense carbonates and interbedded shales in much of the interval should provide adequate seals where unfractured. Areas near faults, especially in the Rome Trough, may be fractured. A lone completion in Webster County also suggests there may be fracture porosity near faults in western Kentucky. In some areas, small, discrete fracture-related porosity zones in the Middle-Upper Ordovician carbonate interval might be used as part of an openhole completion with underlying St. Peter or Knox reservoirs, if these were encountered at more than 2,500 ft depth. Based on known completions in deeper parts of the basins, fracture porosity in this interval occurs near faults. Injection near faults would likely require demonstrating that the faults are sealing above the planned injection reservoirs. Also, openhole injections into multiple horizons would complicate monitoring of injected plumes. Areas where this interval is more than 2,500 ft deep are southeastern Kentucky and parts of the Rough Creek Graben.

Upper Ordovician Shale and Carbonates

CO_2 unit type: primary confining unit (seal)
KGS stratigraphic code: 361ALCK, 361BLFK, 361CLFR, 361CMBD, 361DRKS, 361FRVW, 361GRLK, 361JUNT, 361KOPE, 361LPRS, 361MQKT, 361MRBG, 361ODVCU, 361RDVL

Table 4.5. Wells with reported completions in the Middle-Upper Ordovician carbonate interval, arranged by depth. Depths shown indicate range of reported completions in this interval for all wells in the field. Some wells have multiple completions in this interval. See Figure 4.55 for field locations. Geophysical logs and well records for these completions can be viewed online at the KGS Oil and Gas Database.

No. of Wells with Completions	*Depth (ft)*	*Example KGS Record Nos.*	*Field*	*Units with Completions*	*County*
1	4,811–4,826	28621	Sebree Springs	Trenton	Webster
1	4,550	130969	unnamed	Wells Creek	Leslie
1	4,420	8423	Stephens	High Bridge	Elliott
1	4,150–4,500	49943	Mima	High Bridge	Morgan
2	3,750–3,970	128994, 129410	Royalton	High Bridge	Magoffin
1	3,710–3,906	128244	Lakeville	High Bridge	Magoffin
3	3,706–4,150	11207, 11208	Mine Fork	High Bridge	Johnson, Magoffin
2	3,556–3,670	79597, 71249	Canyon Falls	Wells Creek	Lee
1	3,500–3,715	120833	Boho	High Bridge	Clay
1	3,476–3,496	120018	unnamed	High Bridge	Clay
1	3,318–3,326	78497	Oneida Cons.	Murfreesboro*	Clay
1	3,272–3,278	85655	Fairview	Trenton	Whitley
1	3,140–3,170	122106	Big Branch East	High Bridge	McCreary
1	3,130–3,170	106857	Midsprings School	Murfreesboro*	Whitley
2	3,100–3,940	128989	Holliday	High Bridge, Lexington	Magoffin
7	2,595–3,359	123743, 127631	Jellico Creek North	High Bridge, Murfreesboro*, Wells Creek	Whitley
2	2,903–3,160	125687, 128969	Marsh Creek	Murfreesboro*	McCreary
1	2,900–2,910	108330	Meadow Creek	Lexington	Knox, Whitley
7	2,800–3,949	124666, 114049	Homer (Isonville Cons.)	High Bridge, Trenton, Garrard	Elliott, Lawrence
1	2,765–2,768	28524	Little Goose	Stones River*	Clay
11	2,765–3,905	72661, 75074	Burning Springs Cons.	High Bridge, Murfreesboro*, Stones River*, Wells Creek	Clay
10	2,764–3,965	128020, 106591	Jellico Creek	High Bridge, Lexington, Stones River*, Wells Creek	Whitley
1	2,758–2,764	115634	Walker Creek Cons.	High Bridge	Wolfe
2	2,720–2,970	102147, 52809	Raccoon Mountain	Trenton	Clay, Laurel
1	2,632–2,792	120450	Big Sinking	High Bridge, Wells Creek	Lee
7	2,620–3,652	110055, 3537	Trixie Cons.	Murfreesboro*, Stones River*, Trenton, Wells Creek	Clay
1	2,600–2,618	43557	Billey Fork South	High Bridge	Lee
2	2,580–2,586	108330, 114911	Meadow Creek Cons.	Lexington, Trenton	Whitley
5	2,535–3,256	3539, 28529	Teges Creek	High Bridge, Murfreesboro*, Trenton	Clay
1	2,510–2,520	107710	Island Creek	Stones River*	Owsley

*Murfreesboro is a Tennessee term used by drillers that is equivalent to the Camp Nelson part of the High Bridge Group; Stones River is a Tennessee term equivalent to the High Bridge and Wells Creek.

Series/system: Ordovician
Thickness: 0–580 ft
Distribution: statewide (crops out in central Kentucky)
Number of wells with completion: 1,803
Number of wells that TD: 4,761
Approximate number of wells drilled through unit: 16,109

Interval Definition. The Upper Ordovician shale and carbonate interval consists of shales and limestones from the top of the Lexington (Trenton) Limestone to the unconformity at the base of the Silurian, which is the base of the Brassfield or Sexton Creek Formation in western Kentucky, and the base of the Brassfield or Tuscarora Sandstone in eastern Kentucky (Figs. 4.4–4.5). The shale-dominant parts of the interval are the Maquoketa Shale in western Kentucky, and the Kope, Clays Ferry, Utica, and Point Pleasant Formations in central and parts of eastern Kentucky. In some parts of eastern Kentucky, the West Virginia nomenclature for these shales may be used, including the Reedsville, Martinsburg, and Juniata Formations (Figs. 4.4–4.5). Parts of this interval would be equivalent to the Utica Shale in Ohio, Pennsylvania, and West Virginia. In the subsurface, the Maquoketa is often delineated in western Kentucky, but in eastern Kentucky, if drillers pick a top in this interval they call it Upper Ordovician, Ordovician, Clays Ferry, or Kope somewhat arbitrarily. There is no formal designation of this interval of mixed shale and carbonates in the subsurface across most of eastern Kentucky.

General Description. The Upper Ordovician shale and carbonate interval crops out at the surface in the Bluegrass Region of central Kentucky. Isopach and structure maps have not been completed for this interval. Preliminary data, however, indicate that it varies in thickness from 200 to 300 ft in central Kentucky, 200 to 450 ft in eastern Kentucky, and 300 to more than 400 ft in western Kentucky. A northeast-southwest trend of thick shale in western Kentucky corresponds to the position of the Sebree Trough (see description in Middle-Upper Ordovician carbonates section) (Schwalb, 1980; Kolata and Graese, 1983; Kolata and others, 2001). East of the Sebree Trough, the dark shales of the Maquoketa interfinger with lighter-colored, gray, calcareous shales of the Clays Ferry Formation onto the Jessamine/Lexington Dome in central Kentucky. In central Kentucky, the Clays Ferry and Kope Formations thin as the underlying Lexington Limestone thickens. The Clays Ferry and Kope Formations are overlain by a series of thin limestones and interbedded limestone and shale units that are variably defined in central Kentucky where they are exposed at the surface (see Cressman, 1973; Weir and others, 1984; McDowell, 1986a).

The dark shales of the Maquoketa are partly organic-rich in the Illinois Basin. Chou and others (1991) reported total organic carbon values of 0.1 to 7.26 percent for 341 samples from Illinois and Indiana. They inferred that the Maquoketa had limited source-rock capabilities. Guthrie and Pratt (1994, 1995) noted two organic-rich cycles in the Maquoketa of Illinois and Indiana with 500 to 1,000 mg hydrocarbon/TOC ratios. They concluded that the Maquoketa was the source rock for oils in dolomitized and fractured Trenton oils in Illinois and Indiana.

Sample descriptions from wells drilled through the Maquoketa in western Kentucky are available for the Conoco No. 1 Turner well, McLean County; the Exxon No. 1 Duncan well, Webster County (called Conasauga in formation record); and Texas Gas Transmission No. 1 Shain well, Grayson County. These descriptions can be accessed online at the Kentucky Geological Survey's Oil and Gas Database.

Known Reservoirs or Types of Porosity. Gas has been produced locally from fractured shales and limestones in this interval. Relative to carbon storage, however, the unit has been identified as the primary confining unit of Midwest Cambrian-Ordovician aquifers (Eaton and Bradbury, 1988; Imes, 1988; Young, 1992; McGarry, 1996; Eaton, 2001), including the phase I findings of the Midwest Geological Sequestration Consortium and Midwest Regional Carbon Sequestration Partnership carbon-sequestration partnerships (Frailey and others, 2005; Wickstrom and others, 2005).

Overlying Sealing/Confining Units. Numerous authors have concluded that the Maquoketa (western Kentucky and Illinois Basin) is a confining unit for underlying Cambrian-Ordovician aquifers (see references in Young [1992]). Vertical hydraulic conductivities in the shale in the northern Midwest range from 4.3×10^{-4} to 6.9×10^{-7} ft/day. In a regional model of the Maquoketa confining unit, Mandle and Kontis (1992) estimated a vertical hydraulic conductivity of 6.0×10^{-11} ft/sec. This interval is a primary confining unit for underlying Cambrian and Ordovician reservoirs in both the Illinois and Appalachian Basins. Although published source-rock data from the Illinois Basin have not included samples from western Kentucky, the Maquoketa contains dark brown to black shales that are probably organic-rich. Where these occur in the Sebree Trough and west of the trough, adsorbtive mechanisms relative to CO_2 storage are possible, which would increase the interval's confining abilities in western Kentucky. East of the Sebree Trough, the shale interval changes to a lighter gray and more bioturbated shale with decreasing organic content.

In central Kentucky, the Upper Ordovician shale interval is mostly too shallow or exposed at the surface to be an adequate seal. In eastern Kentucky, the interval consists of alternating limestone and shale, rather than the thick shales that occur in western Kentucky, so it has different confining characteristics than the Maquoketa. In areas where the interval is unfaulted, and contains thick shales, it could have good confining characteristics, but more work is needed on this interval in eastern Kentucky.

CO_2 Storage Potential. The Upper Ordovician shale and carbonate interval is a seal or confining interval. Although numerous wells have produced from parts of this unit, most producing wells are small, local, and were drilled at shallow depths. At depth, it has little or no carbon-storage potential.

Silurian and Devonian Carbonates and Shales

CO_2 unit type: possible local reservoirs and secondary confining unit
KGS stratigraphic code: 357BRSF, 357CBOC, 357CLNT, 355LCKP, 351CORN, 351DCTR, 355LCKP, 351SALN, 355LSVL, 355NGRN, 344DCCK, 344CORN, 344SLBG, 344JFVL
Series/system: Silurian and Devonian
Thickness: 0–2,900
Distribution: eastern and central Kentucky
Number of wells that TD: 23,908
Number of wells with completion: 8,367
Approximate number of wells drilled through unit: 20,870

Interval Definition. The Silurian-Devonian carbonate and shale interval contains all strata from the top of the Brassfield Dolomite, or where the Brassfield is missing, the top of the Upper Ordovician, to the base of the Devonian (New Albany–Ohio–Chattanooga) black shale (Figs. 4.4–4.5). It includes limestone, dolomite, shale, and sandstone, but for the purposes of this report, major sandstones, including the Clinton, Big Six, and Oriskany are excluded from this interval and treated separately in the pages that follow the larger interval's description. The base of the interval is sharp and unconformable with underlying Ordovician shales. Likewise, the top is sharp and unconformable with overlying Devonian black shales. In parts of central Kentucky, the Devonian shales may rest directly on Ordovician carbonates, and this interval is absent.

General Description. The Silurian-Devonian carbonate and shale interval is exposed at the surface along the margins of the Bluegrass Region in central Kentucky. The interval contains a series of carbonates, shales, and sandstones that are irregular in thickness and distribution and influenced by multiple unconformities (Figs. 4.4–4.5). Individual units in this interval are described in Freeman (1951), Peterson (1981, 1986) McDowell (1983), Currie and MacQuown (1984), Seale (1985), and Kepferle (1986). Isopach and structure maps are not provided for this interval.

In general, the interval between the base of the Silurian Brassfield Dolomite or Clinton (Rose Hill) Shale and base of the Ohio Shale is thinnest on the Cincinnati Arch in central Kentucky where it occurs at the surface, and thickens into the basins to the east and west. In south-central Kentucky, the entire interval is truncated beneath the Chattanooga–New Albany Shale (Cattermole, 1963; Kepferle, 1986; Peterson, 1986). Eastward and westward, the interval thickens to more than 1,500 ft. The interval thins into central Kentucky, because of several internal unconformities and the sub-Devonian shale unconformity (Kepferle, 1986; Peterson, 1986; Hamilton-Smith, 1993).

Most of the carbonates in this interval exhibit low porosity and permeability, except where they are truncated updip by the unconformity at the base of the Devonian black shale. At this truncation, vugular porosity can be developed in the carbonates (for example, the Corniferous production in the Big Sinking and Greensburg Fields). This truncation occurs in both the Appalachian and Illinois Basins, and the amount of missing section increases toward the Cincinnati Arch (Freeman, 1951; Currie and MacQuown, 1984; Meglen and Noger, 1996). Because of the variability in the Silurian and Devonian carbonates preserved beneath the Devonian black shale in different parts of the basins, drillers generally do not attempt to subdivide the carbonates beneath the shale, calling them "Corniferous." The Corniferous tends to include the carbonates between the base of the Devonian shale and the first identifiable unit beneath. In some places, the blue color of the Silurian Laurel Dolomite is distinguishable and the top of the Laurel is the base of the Corniferous. In other areas, the top of the Keefer (Big Six) Sandstone is the base of the Corniferous (see, for example, Currie and MacQuown [1984]). The Lockport Dolomite is the lower part of the Corniferous and is summarized in Smosna (1983).

Known Reservoirs or Types of Porosity. Locations of known Silurian completions from this interval are shown in Figure 4.56 and detailed in Table 4.6. Locations of known Devonian completions from this interval are shown in Figure 4.57 and detailed in Table 4.7. The majority of Devonian completions are shallow, and even the deep completions listed in Table 4.7 straddle the 2,500-ft depth. Only 29 wells have reported completions in Devonian carbonates at more than 3,000 ft, and only nine at more than 4,000 ft. Silurian-Devonian carbonates are major oil and gas producers in Kentucky, and are known to have thick zones of porosity and permeability, but most of the oil and gas produced (and known porosity and permeability) is at very shallow depths, which are unsuitable for carbon storage. The majority of the known production (and porosity) is from the drillers' Corniferous. In most cases, Corniferous production is from the carbonate interval that is beneath (within 150 ft of) the base of the Ohio Shale (eastern Kentucky) or New Albany Shale (western Kentucky) in a given area. Lineaments and fractures may be important to production in some areas (Narotzky and Rauch, 1983).

The deepest completions reported from this interval in the state are in Harlan County (Table 4.6), where one field had porosity in the Brassfield Formation at the base of the interval, and several fields produce from the Silurian Lockport Dolomite. These fields are developed beneath the Pine Mountain Thrust Fault and Devonian Ohio Shale at depths of more than 4,000 ft. On the thrust sheet, there is significant relief on the sub-Devonian Ohio Shale unconformity. Most completions are from single wells, so it is difficult to infer reservoir

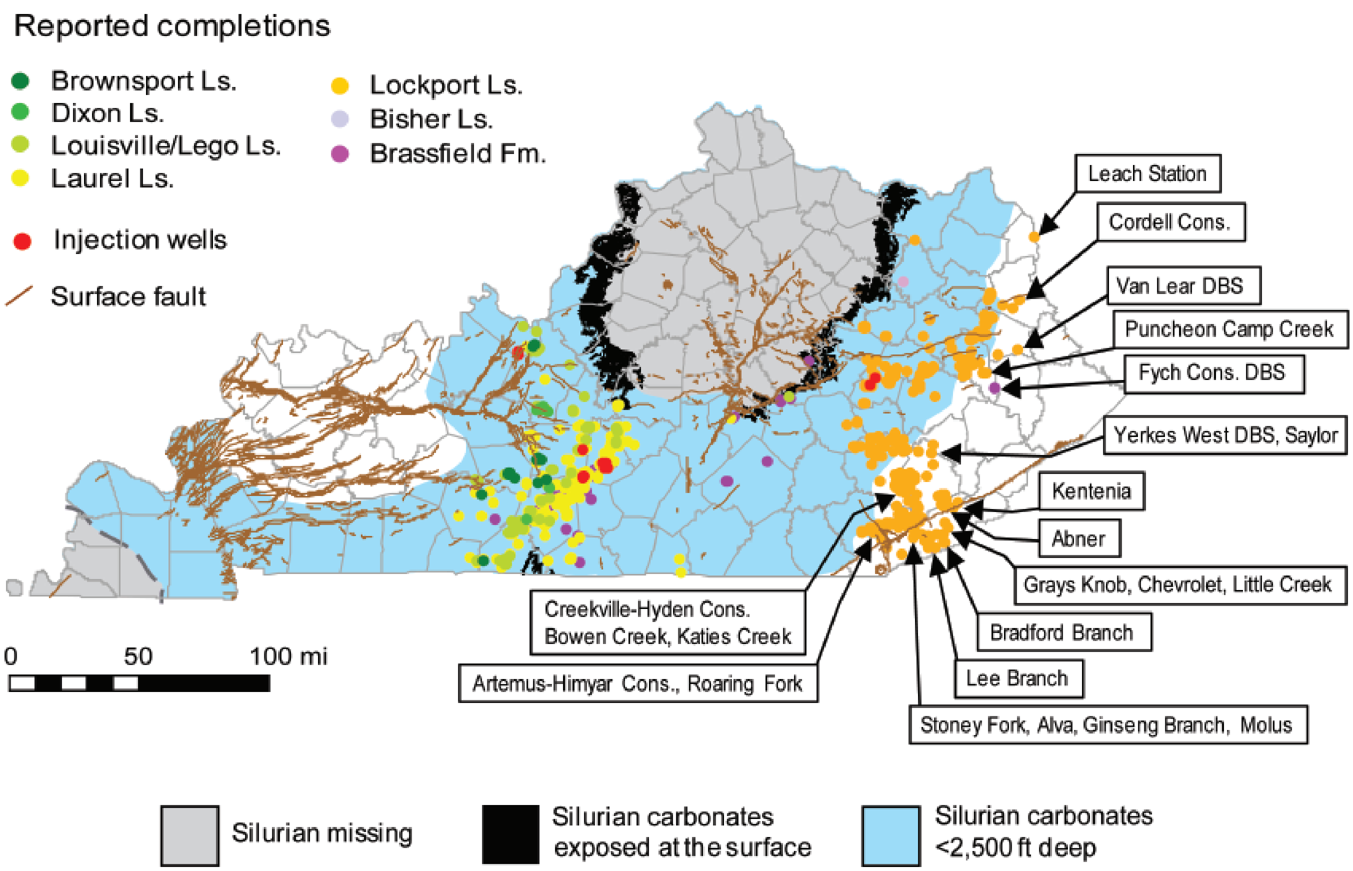

Figure 4.56. Kentucky wells with reported completions in Silurian carbonates. See Figures 4.4 and 4.5 for stratigraphy of the units with well completions in this interval. See Table 4.6 for more information on completions at depths of more than 2,500 ft. Field names in boxes are discussed in the text or listed in Table 4.6. Cons. = Consolidated. DBS = District of Big Sandy Gas Field.

Table 4.6. Wells with reported completions in Silurian carbonates deeper than 2,500 ft. Geophysical logs and well records for these completions can be viewed online at the KGS Oil and Gas Database.

No. of Wells with Completions	*Depth (ft)*	*Example KGS Record Nos.*	*Field*	*Units with Completions*	*County*
3	6,310–4,954	124301, 86827, 120012	Bradford Branch	Brassfield, Lockport	Harlan
1	5,000	123315	Grays Knob	Lockport	Harlan
1	4,884–4,890	91622	Alva	Lockport	Harlan
1	4,823–4,882	86826	unnamed	Lockport	Harlan
1	4,823–4,882	113539	Lee Branch	Lockport	Harlan
1	4,763	127915	Kentenia	Lockport	Harlan
1	4,670	123044	Chevrolet	Lockport	Harlan
1	4,370	123095	Little Creek	Lockport	Harlan
3	4,358–4,758	121773, 123809, 121775	Ginseng Creek	Lockport	Harlan
1	4,300–4,380	120482	Clovertown	Lockport	Harlan
1	4,100–4,122	116068	Hances Creek	Lockport	Bell
1	3,999	123058	Tuggleville	Lockport	Bell
1	3,935	12220	Saylor	Lockport	Leslie
1	3,050	115930	Van Lear District of Big Sandy	Lockport	Johnson
1	3,050	130894	unnamed	Lockport	Leslie
3	3,017–3,945	128046, 122169, 122164	Meadow Branch	Lockport	Bell
7	3,892–4,945	127108, 127544, 128807	Abner	Lockport	Leslie
1	3,799	129599	unnamed	Lockport	Leslie
1	3,766	130665	unnamed	Lockport	Leslie
1	3,679–3,684	126861	unnamed	Lockport	Bell
1	3,656–3,692	89384	Molus	Lockport	Harlan
1	3,614	133431	unnamed	Lockport	Leslie
1	3,606–3,616	127524	unnamed	Lockport	Clay
23	3,599–4,509	126859, 127841, 127252	Stoney Fork	Lockport	Bell, Harlan
1	3,597	123991	unnamed	Lockport	Bell
2	3,569–3,956	127342, 127696	Beverly	Lockport	Bell
1	3,536–3,543	52966	unnamed	Lockport	Leslie
4	3,378–3,636	121954, 127708, 128445	Skidmore	Lockport	Leslie
1	3,377	129260	unnamed	Lockport	Knox
1	3,265–3,271*	129504	Artemus–Himyar Cons.	Lockport	Bell
1	3,122–3,146	129848	unnamed	Lockport	Leslie
4	3,119–3,370	128334, 127859, 131908	Roaring Fork	Lockport	Bell, Knox

*There are more wells in this field with completions in this interval that are less than 2,500 ft deep.

Table 4.6. Wells with reported completions in Silurian carbonates deeper than 2,500 ft. Geophysical logs and well records for these completions can be viewed online at the KGS Oil and Gas Database.

No. of Wells with Completions	*Depth (ft)*	*Example KGS Record Nos.*	*Field*	*Units with Completions*	*County*
1	3,091–3,094	126360	Fych Cons. District of Big Sandy	Brassfield	Magoffin
1	3,031	129530	Turkey Creek	Lockport	Bell
1	2,956–2,970	121034	unnamed	Lockport	Clay
1	2,914–2,970	120616	Cordell Cons.	Lockport	Lawrence
2	2,778–2,904	120858, 120750	Yerkes West District of Big Sandy	Lockport	Leslie
1	2,744–2,786	114403	unnamed	Lockport	Knox
1	2,708–2,718	126451	unnamed	Lockport	Clay
1	2,702	127704	Road Fork District of Big Sandy	middle part of Silurian (undifferentiated)	Knox
1	2,680–2,696	115528	unnamed	Lockport	Leslie
3	2,663–3,168	121713, 131255, 123322	Katies Creek	Lockport	Clay
1	2,638–2,667	75200	Leach Station	Lockport	Boyd
1	2,573–2,695	53240	Toulouse District of Big Sandy	Lockport	Leslie
2	2,566–3,349	128236, 128411	Hyden West Cons.	Lockport	Leslie
7	2,560–2,956	52956, 125025, 52978	Bowen Creek	Lockport	Clay, Leslie
3	2,554–2,594*	120349, 114855, 107317	Puncheon Camp Creek	Lockport	Magoffin
1	2,489–2,604	12331	unnamed	Lockport	Leslie
96	2,422–3,230*	121810, 129393, 12394	Creekville–Hyden Cons.	Lockport	Clay, Letcher
3	2,413–2,588*	121708, 129780, 114367	Oneida Cons.	Lockport	Clay, Owsley

*There are more wells in this field with completions in this interval that are less than 2,500 ft deep.

connectivity, although certainly there is local porosity in this interval in the area.

The Stoney Fork Field of Bell and Harlan Counties and the Creekville–Hyden Consolidated Field of Clay and Letcher Counties have the most completions from this interval on the thrust sheet. Completions are mostly in the Lockport Dolomite (Table 4.6) and Corniferous carbonates (Table 4.7). Several fields have multiple completions in the Silurian and Devonian (Tables 4.6–4.7). In the Stoney Fork Field, the sub-Devonian New Albany Shale unconformity truncates the Silurian-Devonian carbonates to the level of the Lockport Dolomite (more than 170 ft of relief), and porosity is likely developed as a result of dissolution beneath the unconformity and updip pinchout along the unconformity. Similar situations occur in the Creekville Consolidated Field (Clay County), which has 157 completions in the Lockport Dolomite. Ninety-six completions were at depths of more than 2,500 ft (Fig. 4.56, Table 4.6), and 25 of those had multiple completions in the Lockport. Many wells that are completed in the drillers' Big Six sand (Keefer Sandstone; treated separately here) also have completions in the Lockport. The average Lockport completion interval is 25 ft, with a range from 1 to 113 ft. Meglen and Noger (1996) reported that 57 wells were producing from the Lockport at the time of their research, with an average pay thickness of

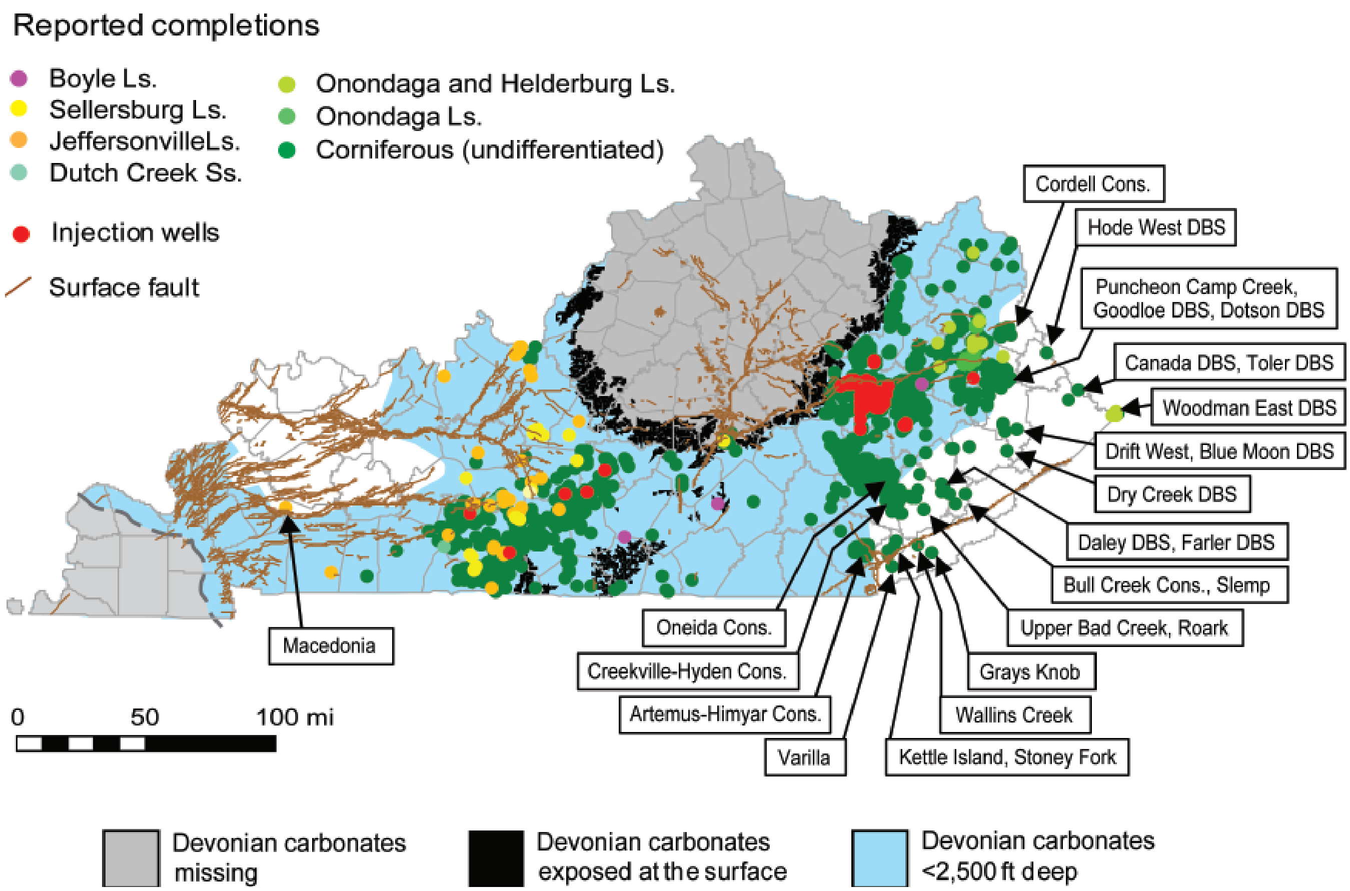

Figure 4.57. Kentucky wells with reported completions in Devonian carbonates. See Figures 4.4 and 4.5 for stratigraphy of the units with well completions in this interval. See Table 4.6 for more information on completions at depths of more than 2,500 ft. Field names in boxes are discussed in the text or listed in Table 4.6. Cons. = Consolidated. DBS = District of Big Sandy Gas Field.

12 ft and average log porosity of 8 percent (range of 4 to 14 percent).

At shallower depths, the Silurian Lockport Dolomite and Devonian Corniferous carbonates have had significant production from the Big Sinking Field of Estill, Lee, Wolfe, and Powell Counties. Although the Big Sinking is too shallow for miscible carbon storage, it is mentioned here because many water injection wells have been drilled in this interval in the Big Sinking Field (Figs. 4.56–4.57). Also, CO_2 was used to repressurize the Lockport Dolomite (Corniferous) in the Big Sinking Field (Price, 1981). Hence, small amounts of CO_2 have already been safely injected into the Lockport in Kentucky. In 2000, the Betragne oil company announced that they had success with a huff and puff process using nitrogen to increase reservoir production in the Big Andy Field, which is next to the Big Sinking Field (Miller and Gaudin, 2000). Carbon dioxide would likely work in a similar fashion, but is currently more expensive than nitrogen. More tests like this are needed to better understand the viability of carbon dioxide floods for enhanced oil recovery in different types of Kentucky reservoirs.

Although many areas have reported completions in this interval in eastern Kentucky, only one was at more than 2,500 ft depth in western Kentucky (Fig. 4.57, Table 4.7). Porosity is developed in the Silurian Brassfield, Louisville, Laurel, and Brownsport Formations at shallow depths on the eastern margin of the Illinois Basin (Fig. 4.56). Likewise, Devonian carbonates such as the Jeffersonville and Sellersburg Limestones have local completions on the eastern side of the basin (Fig. 4.57). A thin Devonian sandstone called the Dutch Creek Sandstone has had production on the southeastern side of the basin in Kentucky (Fig. 4.56). There have also been several water-injection wells in Silurian and Devonian carbonates at shallow depths (Figs. 4.56–4.57). All but one of these

Table 4.7. Wells with reported completions in Corniferous and Devonian carbonates deeper than 2,500 ft. DBS = District of Big Sandy Gas Field. Cons. = Consolidated. Geophysical logs and well records for these completions can be viewed online at the KGS Oil and Gas Database.

No. of Wells with Completions	*Depth (ft)*	*Example KGS Record Nos.*	*Field*	*Field Also Has Silurian Carbonate, Clinton, or Big Six Completion*	*County*
7	5,004–5,474	121464, 123060, 109260	Woodman East District of Big Sandy	Clinton	Pike
1	4,417–4,484	87268	Grays Knob	Silurian carbonate	Harlan
1	4,078–4,106	106302	Canada District of Big Sandy	Clinton	Pike
1	3,890–4,019	39394	Toler District of Big Sandy		Pike
1	3,941–3,981	87854	Wallins Creek		Harlan
1	3,847–3,925	76469	Bull Creek Cons.		Perry
1	3,776–3,779	13289	Hode West District of Big Sandy		Martin
1	3,650–3,695	52997	Daley District of Big Sandy		Leslie
1	3,565–3,626	83287	Slemp District of Big Sandy		Perry
1	3,530–3,540	42323	Upper Bad Creek District of Big Sandy		Leslie
2	3,465–4,448	2334, 128043	Stoney Fork	Big Six, Silurian carbonate	Bell
1	3,335–3,338	2658	Macedonia		Caldwell
3	3,350–3,651	52981, 52980, 83327	Farler District of Big Sandy		Leslie
1	3,261–3,318	2277	Varilla		Bell
1	3,152–3,202	56652	Dry Creek District of Big Sandy		Knott
1	3,080–3,404	11274	Carrie District of Big Sandy	Big Six	Knott
4	3,022–3,247	28552, 44477, 54141, 37737	Hyden West Cons. District of Big Sandy	Big Six, Silurian carbonate	Leslie
1	2,991–3,125	32289	unnamed		Leslie
4	2,972–3,510	2292, 2298, 2297, 76987	Kettle Island		Bell
2	2,925–3,097	12228, 12229	Roark		Leslie
2	2,792–2,942	64933, 62661	Cliff District of Big Sandy		Floyd
3	2,723–2,783	81357, 81358, 11199	Buffalo School		Johnson
2	2,692–2,716	63581, 63582	Goodloe District of Big Sandy	Big Six	Floyd
1	2,660–2,700	68179	Chavies		Perry
1	2,594–2,615*	56390	Peabody		Clay
1	2,573–2,695	12351	unnamed		Leslie
1	2,558–2,576	62423	Dotson Cons District of Big Sandy	Big Six	Floyd
4	2,548–3,641	51917, 59935, 59959, 61094	Drift West District of Big Sandy	Big Six	Floyd

*There are more wells in this field with completions in this interval that are less than 2,500 ft deep.

Table 4.7. Wells with reported completions in Corniferous and Devonian carbonates deeper than 2,500 ft. DBS = District of Big Sandy Gas Field. Cons. = Consolidated. Geophysical logs and well records for these completions can be viewed online at the KGS Oil and Gas Database.

No. of Wells with Completions	*Depth (ft)*	*Example KGS Record Nos.*	*Field*	*Field Also Has Silurian Carbonate, Clinton, or Big Six Completion*	*County*
1	2,536–2,556	81363	Welch		Johnson
34	2,496–3,013*	108845, 52976, 104099, 77467	Creekville–Hyden Cons.	Big Six, Clinton, Silurian carbonate	Clay
3	2,496–2,540*	81304, 81336, 81377	Barnetts Creek	Big Six	Johnson
7	2,495–2,882*	84625, 76668, 84623, 84621	Artemus–Himyar Cons.	Clinton, Silurian carbonate	Knox
19	2,470–2,600*	71854, 26752, 89778, 90660	Oneida Cons.	Silurian carbonate	Clay
6	2,237–2,898*	77396, 75185, 77357, 77386	Puncheon Camp Creek	Big Six, Silurian carbonate	Magoffin
1	2,220–2,515*	80708	Beetree		Magoffin
6	2,140–2,862	71944, 71690, 81443, 81446	Van Lear District of Big Sandy	Big Six, Silurian carbonate	Johnson
2	2,140–2,677	63422, 88886	Molly Branch School District of Big Sandy		Floyd
4	1,987–2,868	72921, 76272, 62376, 62377	Whitaker District of Big Sandy		Floyd
34	1,896–2,944*	37669, 50972, 50969, 62512	Cordell Cons.	Big Six, Clinton, Silurian carbonate	Lawrence
2	1,250–2,532*	110687	Oil Springs Cons.		Magoffin

*There are more wells in this field with completions in this interval that are less than 2,500 ft deep.

Silurian-Devonian completions (and all of the injection wells) are at depths of less than 2,500 ft, however. The lone deeper completion is from a single well in the Macedonia Field of Caldwell County, and is reported in a narrow (3 ft) porosity interval in the Devonian Jeffersonville Limestone at a depth of 3,335 ft. Few deep wells penetrate the interval in western Kentucky, but other wells show little evidence of porosity.

Overlying Sealing/Confining Units. In most Brassfield, Lockport, or Corniferous producing wells, the reservoirs are confined by the Devonian black shale or Silurian and Devonian carbonates between the reservoir and the Devonian shale (Meglen and Noger, 1996). Several shales in this interval should also help the unit's sealing characteristics (Figs. 4.4–4.5), where they are unfractured or unfaulted. In eastern Kentucky, the Crab Orchard (Rose Hill) Formation occurs above the Brassfield Dolomite, and is dominated by greenish gray clay shales, with minor dolomite toward the base (McDowell, 1983; Peterson, 1986). This shale, which is called the "Clinton shale" by drillers, is more than 400 ft thick in Pike County and easternmost Kentucky. The equivalent Osgood Formation in central and western Kentucky is significantly thinner (less than 50 ft), but also consists of green-gray (and gray) clay shales and clayey dolomite (McDowell, 1983; Peterson, 1986). The Osgood, Waldron, and Randol Shales are additional thin shales (less than 50 ft) in this interval in parts of western and south-central Kentucky that should aid in the unit's confining characteristics.

CO_2 Storage Potential. The Silurian-Devonian carbonate and shale interval was analyzed as part of a regional confining zone by the Midwest Regional Carbon Sequestration Partnership, and is a seal or confining interval, although numerous areas have local, discrete porous zones that could provide local storage potential. Local porosity is well developed in carbonates downdip from the unconformity beneath the Devonian black shale, but these also tend to be areas in which hydrocarbons are produced. Some of these fields may be able to use CO_2 for secondary recovery (see chapter 3 of this report). Elsewhere, the carbonates and interbedded shales in much of the interval should provide adequate seals where unfractured. Areas near faults may be fractured. Injection near faults would likely require demonstrating that the faults are sealing above the planned injection reservoirs. Regional sandstones that occur within this stratigraphic interval are treated separately below.

Tuscarora (Clinton) Sandstone

CO_2 unit type: possible local reservoirs
KGS stratigraphic code: 357CLNTS
Series/system: Silurian
Thickness: 0–150(?) ft
Distribution: eastern Kentucky
Number of wells with completion: 52
Number of wells that TD: 94
Approximate number of wells drilled through unit: 21,290

Interval Definition. The Tuscarora Sandstone sharply overlies the Upper Ordovician shale interval (Juniata Formation) in West Virginia and easternmost Kentucky and is overlain by the Silurian Brassfield Dolomite or Crab Orchard (Rose Hill) Formation (Figs. 4.4–4.5). The Tuscarora is called the "Clinton" by drillers. In easternmost Kentucky, there may be several sandy intervals in the Rose Hill (which reaches more than 400 ft in thickness), and it seems likely that there may be several Clinton sandstones. For the purposes of this report, the basal Tuscarora and any other sandstones in this interval are considered Clinton. The Clinton as used here does not include the Keefer (Big Six) Sandstone, which overlies the Rose Hill/Crab Orchard Shale. On some drillers' logs in eastern Kentucky, the name "Clinton" was sometimes used erroneously for the Big Six as well. The Keefer (Big Six) Sandstone is treated separately in this report.

General Description. The Tuscarora is well developed in Ohio and West Virginia, and pinches out in eastern Kentucky, prior to exposure of the Silurian strata on the margin of the Cincinnati Arch. Where present in the subsurface of eastern Kentucky, the sandstone is generally fine grained, gray to green-gray, and may be interbedded with clays, hematite, and glauconite (Watson, 1979). An isopach map was not made for this interval, but data from completion records indicate that the sandstone varies from 0 to 150 ft thick. The thick completions do not indicate a 150-ft sandstone, however. Rather, the thick completions seem to be cases of multiple Silurian sands separated by shales. Individual sandstones in the net completions are usually less than 30 ft thick. As with other units, the Tuscarora (Clinton) is deepest in eastern Pike County (6,200 ft depth) and shallows westward (Fig. 4.58). A separate structure map was not constructed for this interval, but structure lines are included in Figure 4.58.

Known Reservoirs or Types of Porosity. There are 229 reported Clinton completions in eastern Kentucky. The Clinton produces from several fields in southeastern Kentucky in Whitley, Knox, and Bell Counties (west of Pine Mountain), is a target in the Middlesboro Syncline (east of Pine Mountain) beneath the thrust fault in the Devonian black shale, and has produced as far north as the Ashland (previously Clinton) Field in northeastern Kentucky (Fig. 4.58, Table 4.8). One completion is in the Chestnut Field of Bell and Knox Counties at a depth of 2,679 to 3,196 ft (Table 4.8). Nine completions have been reported in the Bradford Branch Field in Harlan County (Middlesboro Syncline) at depths of 4,902 to 6,272 ft. A report by Watson (1979) on the Clinton (now Ashland) Field in Boyd County indicates that the sandstone was fine-grained, 5 to 12 ft thick, and thickened across a fault in northeastern Kentucky. Depth to the producing interval was approximately 2,800 to 3,050 ft. Log porosity of the primary producing zone was 5 to 12 percent (Watson, 1979). Across the state line in Wayne County, W.Va., several wells had high nitrogen content (23 percent) in the Clinton sand. In central West Virginia, gas analyses from several Clinton wells showed naturally high CO_2 levels (Patchen, 1968b).

Overlying Sealing/Confining Units. The thick shales of the Crab Orchard (Rose Hill) Formation would be the immediate seal where they overlie the Clinton sandstone in parts of eastern Kentucky (Figs. 4.4–4.5). Where overlying Silurian-Devonian carbonates are preserved between the Clinton and sub-Devonian shale unconformity, they would serve as a secondary confining interval. In southeastern Kentucky and in parts of the Middlesboro Syncline of Harlan County, the sub-Devonian shale unconformity removes the Silurian-

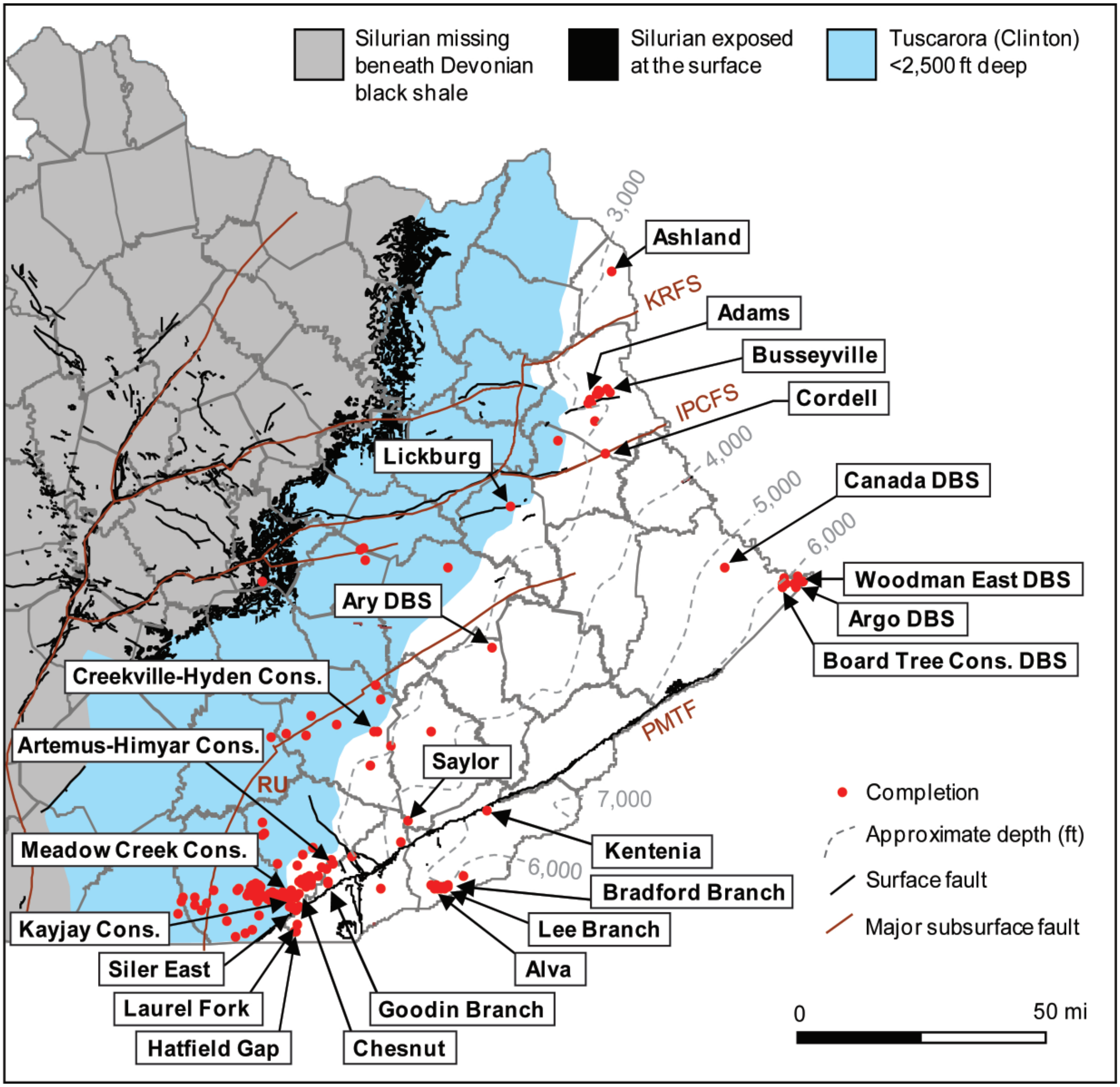

Figure 4.58. Wells reporting Clinton completions in Kentucky and preliminary contours of depth to the top of the Tuscarora (Clinton) Sandstone. Cons. = Consolidated. DBS = District of Big Sandy Gas Field. KRFS = Kentucky River Fault System. IPCFS = Irvine–Paint Creek Fault System. PMTF = Pine Mountain Thrust Fault. RU = Rockcastle Uplift. See Table 4.8 for more information on completions at depths of more than 2,500 ft. Field names in boxes are discussed in the text or listed in Table 4.8.

Devonian carbonate section. The ultimate confining interval would be the Devonian Ohio (Chattanooga) Shale, which should be at sufficient depths to be a seal in most parts of easternmost Kentucky in which the Tuscarora (Clinton) would have porosity. More work may be needed in evaluating the influence of the Pine Mountain Thrust Fault on seal integrity in the Middlesboro Syncline (Harlan County) where the Clinton may locally have adequate porosity for carbon storage. Because many wells have been drilled through this unit, poor seal integrity as a result of well penetrations might be a concern in some parts of eastern Kentucky. If sec-

Table 4.8. Wells and fields with reported completions in the Tuscarora (Clinton) Sandstone at depths of more than 2,500 ft. Geophysical logs and well records for these completions can be viewed online at the KGS Oil and Gas Database.

No. of Wells with Completions	*Depth (ft)*	*Example KGS Record Nos.*	*Field*	*County*
1	6,180–6,254	111874	Argo District of Big Sandy	Pike
3	6,074–6,478	123059, 109229, 109228	Woodman East District of Big Sandy	Pike
1	5,924–5,928	9928	Kentenia	Harlan
5	5,850–6,568	108012, 108189, 121574	Board Tree Cons. District of Big Sandy	Pike
1	5,813	129809	unnamed	Harlan
1	5,543–5,612	107111	Canada District of Big Sandy	Pike
1	5,246–5,254	123404	Alva	Harlan
4	5,238–6,668	113539, 122205, 121937	Lee Branch	Harlan
9	4,902–6,272	122115, 124301, 124533	Bradford Branch	Harlan
1	4,495	128859	Saylor	Leslie
1	3,934	126441	unnamed	Pike
2	3,754–3,944	126864, 126869	Hatfield Gap	Bell
1	3,563–3,567	50748	Busseyville	Lawrence
1	3,474–3,495	131722	unnamed	Johnson
1	3,406–3,414	120026	Laurel Fork	Bell
1	3,360–3,780	121030	unnamed	Bell
1	3,316	121133	Poplar Creek	Knox
7	3,300–3,650	108668, 50717, 50752	Adams	Lawrence
1	3,198–3,200	2355	Ashland	Boyd
1	3,125–3,151	32289	unnamed	Leslie
1	3,082–3,096	78781	Ary District of Big Sandy	Perry
4	2,557–3,114*	125857, 127216, 121822	Meadow Creek Cons.	Bell, Knox, Whitley
1	2,994–2,998	115048	Kayjay Cons.	Whitley
1	2,955	62500	Cordell	Lawrence
3	2,584–3,278	122244, 120468, 121482	Siler East	Whitley
2	2,694–3,350	126207, 127010	Goodin Branch	Bell
15	2,679–3,196	115244, 114108, 115588	Chestnut	Bell, Knox
1	2,673	129956	Jellico Creek	Whitley
4	2,530–3,143*	120068, 123350, 125621	Artemus–Himyar Cons.	Knox
1	2,505	124707	Lickburg	Magoffin
4	2,495–2,872	103870, 130128, 114737	Creekville–Hyden Cons.	Clay

*There are more wells in this field with completions in this interval that are less than 2,500 ft deep.

ondary recovery using carbon dioxide is ever attempted in these areas, information about well locations and plugging will be critical to prevent or mitigate potential leakage of any injected CO_2 up old wellbores.

CO_2 Storage Potential. Wickstrom and others (2005) estimated the Tuscarora (Clinton) Sandstone to be more than 2,500 ft deep in approximately 420 mi^2 in Kentucky and calculated potential volumetric storage capacity of 1.0 billion short ton (0.89 billion metric ton) in the phase I report of the Midwest Regional Carbon Sequestration Partnership. If only 4 percent of that volume has storage potential, 39.2 million short tons

(35.6 million metric tons) could be stored; if 1 percent, then 9.8 short tons (8.9 million metric tons) would be available. The Clinton is a more important reservoir to the north and east in Ohio and Pennsylvania. In fields around that region, Clinton wells are hydraulically fractured to increase production (Wickstrom and others, 2005). Areas near faults may be naturally fractured. Injection near faults would likely require demonstrating that the faults are sealing above the planned injection reservoirs.

Keefer (Big Six) Sandstone

CO_2 unit type: possible local reservoirs
KGS stratigraphic code: 355BGSX, 355KEFR
Series/system: Silurian
Thickness: 0–63 ft
Distribution: eastern Kentucky
Number of wells with completion: 912
Number of wells that TD: 424
Approximate number of wells drilled through unit: 26,905

Interval Definition. The Keefer Sandstone sharply overlies the Crab Orchard (Rose Hill) Formation in eastern Kentucky (Figs. 4.4–4.5). In much of eastern Kentucky, the Keefer is overlain by the Lockport Dolomite, or westward, where the Lockport is truncated by the sub-Devonian shale unconformity (e.g., in Powell County) by the Ohio Shale. The Keefer is called the "Big Six" by drillers. The interval discussed in this report is the same as the formal formation, which is generally the same as the drillers' designation.

General Description. The Keefer is a tan to brown, locally greenish tan, poorly to well-sorted, very fine- to medium-grained, subangular to rounded sandstone, with local quartz-pebble conglomeratic beds. The sandstone sharply overlies Silurian Crab Orchard (Rose Hill) shales. The Keefer is coarsest in southeastern Kentucky and becomes finer grained and more dolomitic northward into east-central and northeastern Kentucky (Currie, 1981). The sandstone is interpreted to have been deposited in coastal marine and shallow marine settings (Smosna, 1983; Meyer and others, 1992).

Isopach and structure maps were not constructed for this interval. According to the Kentucky Geological Survey Oil and Gas Database, the sandstone is 0 to 63 ft thick. Previous investigations have indicated that it is thickest in Breathitt and Magoffin Counties, in the Rome Trough (Currie and MacQuown, 1984; Zelt, 1994). It thins westward onto the Cincinnati Arch, northward into Lawrence and Elliott Counties, and southward into Pike, Floyd, Knott, and Letcher Counties. The sandstone may be missing locally, and becomes a sandy carbonate eastward. In much of eastern Kentucky, the sandstone is less than 2,500 ft deep, including in the areas of thick sand development in Breathitt and Magoffin Counties.

Known Reservoirs or Types of Porosity. Completions (and therefore porosity) have been reported in nearly 900 wells in eastern Kentucky in the Keefer (Big Six) Sandstone (Fig. 4.59); in 220 completions, the base of the Big Six was more than 2,500 ft deep (Table 4.9). The first gas was discovered at the Taulbee Consolidated Field by the Big Six Gas Co., from which the drillers' name for the unit is derived (Hunter, 1955). A cross section across the field (Fig. 4.60) shows multiple porosity intervals within the sandstone, and the lateral extent of porosity zones in the field. Most fields have small size and produce from sandy dolomites in stratigraphic-structural traps (Noger and others, 1996). Lineaments and fractures may be important to production in some areas (Narotzky and Rauch, 1983). Some fields produce from the Big Six and overlying Lockport Dolomite (Table 4.9).

Log porosities in Keefer (Big Six) producing zones range from 3 to 28 percent (average 12 percent), and the average permeability based on five cores in three fields was 7.06 md (0.81 to 50 md). Nine fields were summarized in Noger and others (1996), and two of those fields, Cordell Consolidated and Auxier District of the Big Sandy Gas Field, produce from depths greater than 2,500 ft. Two fields in Wayne County, W.Va., just across the river from Boyd County, Ky., also produce from the Keefer at depths greater than 2,500 ft (Patchen, 1968a). Noger and others (1996) reported that intergranular (possibly primary) porosity is enhanced by dissolution of cement and feldspars in most producing fields, and that cements are mostly quartz overgrowths in coastal sand facies and ankerite in marine shelf sands. Smosna (1983) noted that the porosity of the Keefer in West Virginia was generally low (1 to 6 percent) because primary pore space has been occluded by at least two generations of cement and dolomite. Local, minor secondary porosity is caused by partial dissolution of calcite grains and cement (Smosna, 1983).

Aside from the reported oil and gas completions, there are five reported injection wells in the Keefer

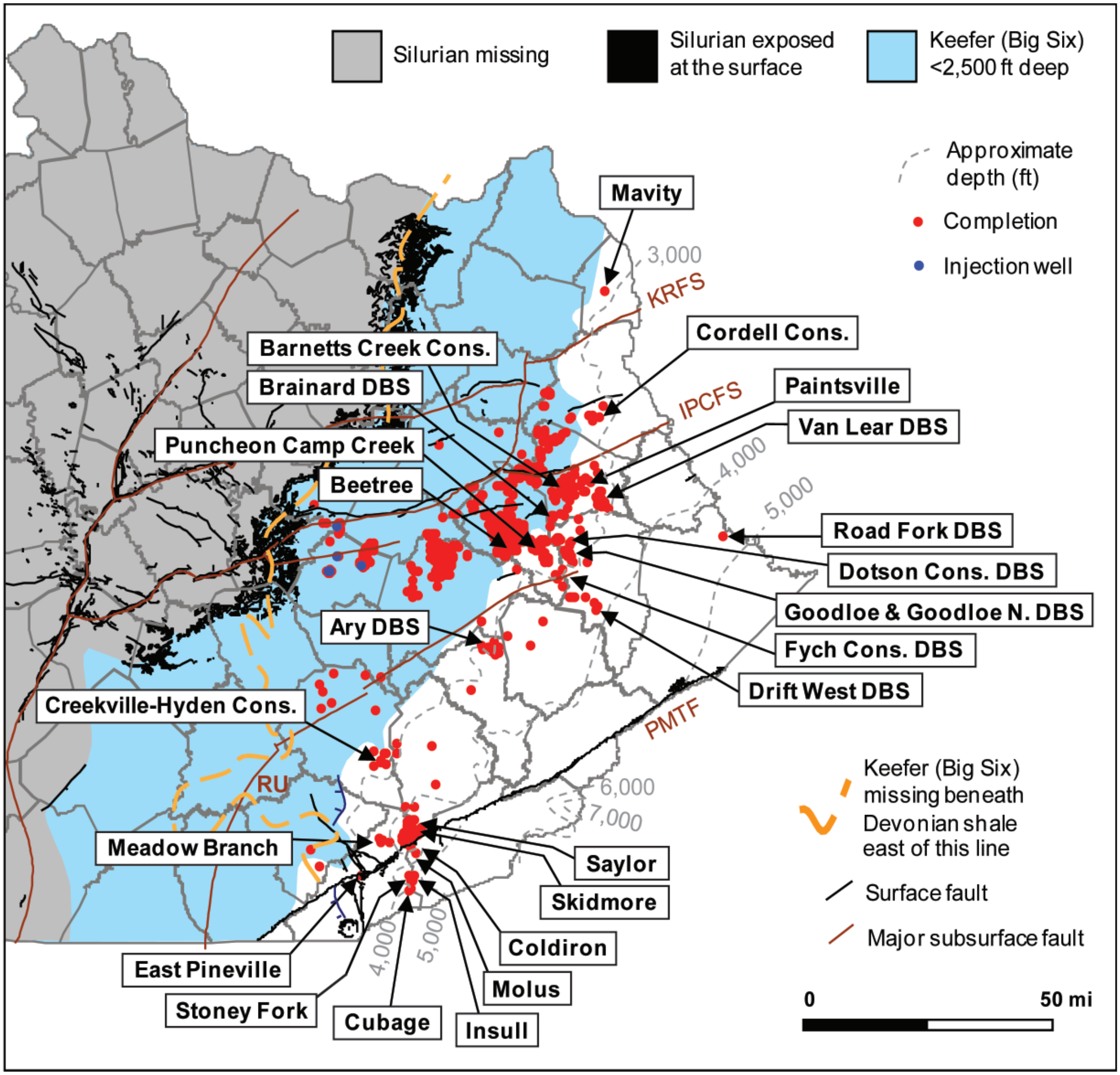

Figure 4.59. Kentucky wells with reported completions of more than 2,500 ft depth in the Keefer (Big Six) Sandstone. Cons. = Consolidated. DBS = District of Big Sandy Gas Field. KRFS = Kentucky River Fault System. IPCFS = Irvine–Paint Creek Fault System. PMTF = Pine Mountain Thrust Fault. RU = Rockcastle Uplift. See Table 4.9 for more information on completions at depths of more than 2,500 ft. Subcrop line after Meglen and Noger (1996, Fig. DSu-6). Field names in boxes are discussed in the text or listed in Table 4.9.

Sandstone in Lee County: three injection wells in the Big Sinking Field, one in the Contrary Creek Field, and one in the Union Church Field. All of these wells are relatively shallow (less than 1,300 ft), and all are water-injection wells. Injection volume and rate data are not currently available from these wells.

Overlying Sealing/Confining Units. Seals in known Big Six reservoirs are the immediately overlying impermeable parts of the Keefer and the overlying Lockport Dolomite (Figs. 4.4–4.5). The New Albany Shale would be the ultimate seal. Because of the many wells drilled through this unit, poor seal integrity as a result

Table 4.9. Fields with reported completions in the Keefer (Big Six) at depths of more than 2,500 ft. Geophysical logs and well records for these completions can be viewed online at the KGS Oil and Gas Database.

No. of Wells with Completions	*Depths (ft)*	*Example KGS Record Nos.*	*Field*	*Field Also Has Silurian Completions*	*County*
1	4,530–4,531	104509	Road Fork District of Big Sandy	X	Pike
2	4,262–5,324	123990, 124141	Cubage		Bell
1	4,071	129128	Skidmore	X	Leslie
6	4,036–4,450	120220, 1214754, 121892	Insull		Bell, Harlan
6	3,882–4,403	110137, 128859, 130596	Saylor	X	Leslie
1	3,861	127686	Coldiron		Harlan
1	3,838	127510	East Pineville		Bell
16	3,626–4,562	126859, 127252, 126440	Stoney Fork	X	Bell, Harlan
2	3,768–4,123	126905, 127224	Molus	X	Bell, Harlan
1	3,743–3,748	121774	unnamed		Harlan
1	3,713–3,719	126861	unnamed		Bell
1	3,559	126048	unnamed		Leslie
3	3,502–3,517	121289, 121287, 121590	Meadow Branch	X	Bell
1	3,441	128236	Hyden West Cons.	X	Leslie
1	3,414–3,428	87825	Marion Branch		Leslie
1	3,412–3,417	47015	Balls Fork District of Big Sandy		Knott
1	3,404–3,428	11274	Carrie District of Big Sandy		Knott
1	3,274–3,300	64132	Chestnut Lick Branch District of Big Sandy		Floyd
1	3,183–3,220	103624	Rockhouse Branch District of Big Sandy		Knott
10	3,072–3,307	121967, 113501, 126361	Fych Cons. District of Big Sandy	X	Magoffin
4	3,066–3,661	121621, 8670, 52254	Drift West District of Big Sandy		Floyd
1	2,932–2,972	122212	unnamed		Johnson
1	2,898–2,905	101018	unnamed		Breathitt
1	2,893–2,932	74885	Molly Branch School District of Big Sandy		Magoffin
2	2,860–2,882	131170, 132571	Mingo School District of Big Sandy		Johnson
1	2,781–2,815	62657	Whitaker District of Big Sandy		Magoffin
1	2,765	2765	Bend Road		Knox
2	2,747–2,822	11199, 81357	Buffalo School		Johnson
13	2,744–3,090	81445, 71903, 71906	Van Lear District of Big Sandy	X	Johnson
1	2,740–2,790*	45967	Elna Cons.		Johnson
1	2,720–2,740	63337	Goodloe District of Big Sandy		Floyd

*There are more wells in this field with completions in this interval that are less than 2,500 ft deep.

Table 4.9. Fields with reported completions in the Keefer (Big Six) at depths of more than 2,500 ft. Geophysical logs and well records for these completions can be viewed online at the KGS Oil and Gas Database.

No. of Wells with Completions	*Depths (ft)*	*Example KGS Record Nos.*	*Field*	*Field Also Has Silurian Completions*	*County*
1	2,712	125750	Bowen Creek	X	Clay
11	2,700–3,123	89172, 80167, 80214	Ary District of Big Sandy		Perry
6	2,693–3,082	63505, 88399, 63412	Goodloe North District of Big Sandy		Floyd
1	2,670–2,700	75154	Fredville		Magoffin
6	2,600–2,984	37660, 49628, 37674	Cordell Cons.	X	Lawrence
1	2,584–2,614*	121951	Swamp Branch		Johnson
6	2,560–2,949	122189, 114213, 61771	Dotson Cons. District of Big Sandy		Floyd
1	2,556–2,600	81363	Welch		Johnson
4	2,555–2,712*	92687, 100394, 81365	Paintsville		Johnson
5	2,552–2,808	61753, 67155, 61716	Brainard District of Big Sandy		Floyd
9	2,544–3,084	121927, 131592, 123452	Creekville–Hyden Cons.	X	Leslie
33	2,528–2,968*	15989, 75122, 75152	Puncheon Camp Creek Cons.	X	Johnson, Magoffin
2	2,518–2,550	133293, 130958	Blevins		Lawrence
1	2,515–2,585	75215	Mavity		Boyd
1	2,502–2,546	86951	unnamed		Johnson
1	2,486–2,503*	76053	Noble		Breathitt
1	2,464–2,608	125696	unnamed		Magoffin
1	2,465–2,525	60615	Stevenson		Breathitt
11	2,449–2,770*	36455, 81304, 37116	Barnetts Creek Cons.		Johnson
23	2,430–2,822*	126175, 80940, 130101	Beetree		Breathitt, Magoffin
6	2,400–2,855*	123561, 126715, 125577	Royalton		Magoffin
2	2,400–2,615*	126534, 126838	Lakeville		Magoffin

*There are more wells in this field with completions in this interval that are less than 2,500 ft deep.

of well penetrations might be a concern in some parts of eastern Kentucky. Most of the areas of concentrated drilling into the Big Six are at shallow depths, where it is unlikely large-volume carbon storage would ever be attempted. If secondary recovery using carbon dioxide is ever attempted in these areas, information about well locations and plugging will be critical to prevent or mitigate potential leakage of any injected CO_2 up old wellbores.

CO_2 Storage Potential. The sandstone is at depths of more than 2,500 ft in only the easternmost part of the state. An assessment of the storage capacity of the Keefer Sandstone is currently under way as part of the phase II research of the DOE-sponsored Midwest Regional Carbon Sequestration Partnership. Areas in Kentucky for which good porosity data are available are also areas where there is hydrocarbon production, so that competing use of resources and possible dilution of produced gas may be issues, unless CO_2 is used for secondary recovery of hydrocarbons. Aside from these issues, it might be possible to use the Keefer (Big Six) as part of a series of stacked reservoirs to attain the net volume or capacity needed for large-scale storage in some parts of eastern Kentucky. Any test for deeper horizons should certainly consider investigating this sandstone. Areas near faults may be fractured. Injection near faults would likely require demonstrating that

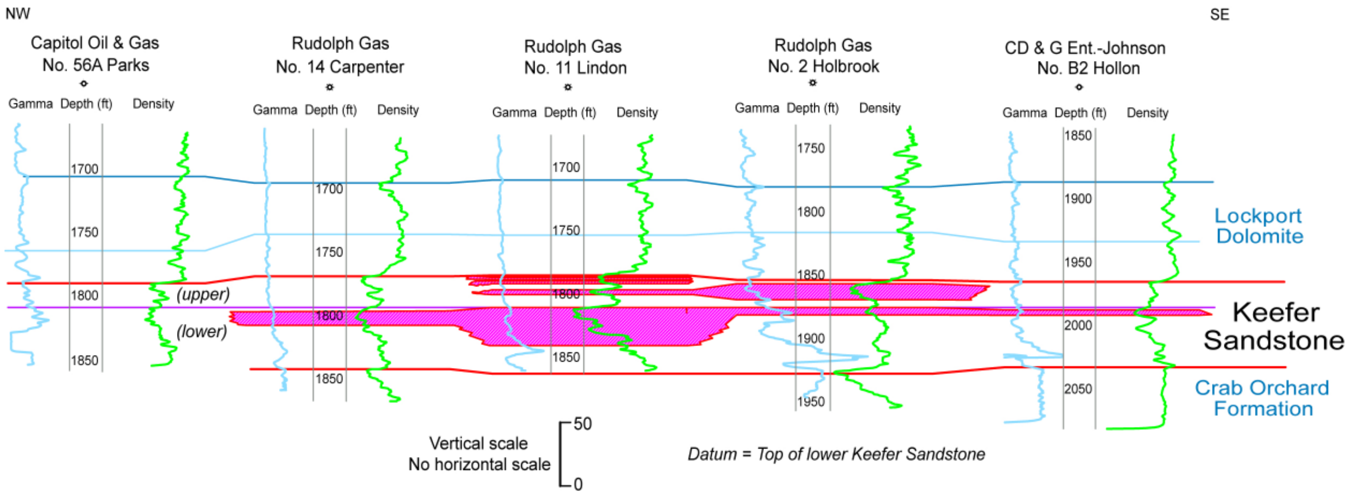

Figure 4.60. Cross section across the Taulbee Consolidated Field in Breathitt County illustrating the upper and lower producing zones (pink) of the Keefer Sandstone (after Noger and others, 1996, Fig. Sld-16). Horizontal distance represents approximately 4.7 mi. Density logs are shown by green lines, gamma-ray logs are shown by light blue lines. The section provides a good example of the lateral variability in known reservoirs within this interval.

the faults are sealing above the planned injection reservoirs.

Oriskany Sandstone

CO_2 unit type: possible regional/local reservoirs
KGS stratigraphic code: 347 ORSK
Series/system: Devonian
Thickness: 0–35(?) ft
Distribution: eastern Kentucky
Number of wells with completion: 14?
Number of wells that TD: 2
Approximate number of wells drilled through unit: 31,209

Interval Definition. In eastern Kentucky, the Oriskany is the sandstone between the Onondaga and Helderberg Limestones (Figs. 4.4–4.5), in the upper part of the Corniferous of drillers' terminology. An unconformity occurs at the base and the top of the sandstone. The interval discussed in this report is the same as the formal formation.

General Description. The Oriskany is a white, quartzose sandstone. It is best developed in West Virginia, Maryland, and Pennsylvania, pinching out to the east beneath an unconformity at the base of the Devonian carbonates. The sandstone has only been confirmed in a few counties in easternmost Kentucky. Harper and Patchen (1996) noted the heterogeneous nature of Oriskany porosity and permeability in Pennsylvania, concluding that the best porosities are near updip pinchouts and in areas of secondary dissolution of carbonate cements along fractures. Similar porosities have not been encountered in Kentucky and in the phase I summary report of the Midwest Regional Carbon Sequestration Partnership, the Oriskany was not mapped except for in the smallest part of eastern Kentucky (Wickstrom and others, 2005). Elsewhere, it is less than 2,500 ft deep.

Known Reservoirs or Types of Porosity. There are 14 reported completions in the Oriskany in Kentucky, and most are shut-in gas wells. Five completions are reported from the Woodman East District of the Big Sandy Gas Field in Pike County, four from the Blevins Field in Lawrence County, three from the Redbush Consolidated Field, one from the Royalton Field in Magoffin County, and one from the Ashland Field in Boyd County. Only wells in the Woodman East Field are at depths of more than 2,500 ft (5,510 to 5,330 ft). The unit is likely not thick enough, permeable enough, or widespread enough to be considered as a large-scale saline aquifer in Kentucky, but locally may be porous, and should be tested if drilled through in tests of deeper horizons in case it locally might have enough porosity to be used as a secondary or tertiary reservoir in a stacked reservoir situation.

Overlying Sealing/Confining Units. The immediate confining interval would be the overlying Devonian carbonates. The ultimate seal would be the Devonian shale (Figs. 4.4–4.5). Because of the large number of wells drilled through this unit, poor seal integrity as a result of well penetrations might be a concern in some parts of eastern Kentucky.

CO_2 Storage Potential. The Oriskany is only distributed across a small part of northeastern Kentucky, and it is too shallow (less than 2,500 ft deep) across a large part of eastern Kentucky to be considered for large-scale carbon storage. The unit's potential volumetric storage capacity was estimated at approximately 20.9 million short tons (19 million metric tons) in the phase I report of the DOE-sponsored Midwest Regional Carbon Sequestration Partnership (Wickstrom and others, 2005). If only 4 percent of that volume has storage potential, 0.8 million short ton (0.76 million metric ton) could be stored; if 1 percent has storage potential, then 0.2 million short ton would be available. The conservative value is probably more realistic given the restricted distribution of the interval and lack of significant porosity in known wells.

Devonian Shale

CO_2 unit type: possible regional/local reservoirs and ultimate/primary confining unit
KGS stratigraphic code: 341CHAT, 341NALB, 341OHIO
Series/system: Devonian
Thickness: 4–1,600 ft
Distribution: eastern, western, and south-central Kentucky
Number of wells with completion: 13,930
Number of wells that TD: 13,044
Approximate number of wells drilled through unit: 44,776

Interval Definition. The Devonian shale includes Upper Devonian shales and thin limestones assigned to the New Albany, Chattanooga, or Ohio Shales in Kentucky (Figs. 4.4–4.5). This interval extends from the base of the sub-shale unconformity to the overlying New Providence, Borden, or Sunbury Formations. The major unconformity at the base of the Devonian truncates both Silurian and Ordovician units; the shales rest on the Upper Ordovician in south-central Kentucky (Cattermole, 1963; Kepferle, 1986).

General Description. The Devonian shale is an organic-rich, gray to brown-black shale, with minor green shale. It is the principal gas producer in the state, the source of much of Kentucky's petroleum resources, and is an oil shale. The shale crops out at the surface in the Knobs Region of Kentucky and dips into the subsurface in eastern and western Kentucky (Fig. 4.61). The top of the shale is more than 2,250 ft below sea level in Pike County (more than 6,000 ft deep) and more than 4,000 ft below sea level in the Webster Syncline of western Kentucky (Fig. 4.61). The thickness of the shale approximately follows the regional structural dip of the shale. It is thinnest on the Cincinnati Arch in central Kentucky (Fig. 4.62), with only 4 ft preserved in south-central Kentucky where the shale rests directly on Ordovician limestones (Cattermole, 1960; Kepferle, 1986). It thickens east and west into the basins on either side of the arch, but thickens significantly more in eastern than in western Kentucky. The shale is more than 1,600 ft thick in easternmost Pike County (Fig. 4.62).

Units recognized within the New Albany Shale in the Illinois Basin were summarized by Cluff and Lineback (1981) for Illinois, Hasenmueller and Woodard (1981) for Indiana, and Schwalb and Norris (1980) for western Kentucky. For eastern Kentucky, maps and summaries of the shale are provided in Schwalb and Potter (1978), Fulton (1979), Pryor and others (1981), Potter and others (1982), deWitt and others (1993), and Boswell (1996). Dillman and Ettensohn (1980a–h) provided isopach maps and structure maps of individual members of the Ohio Shale in eastern Kentucky (1980i–p).

Known Reservoirs or Types of Porosity. The shale is an unconventional gas reservoir, and it is theoretically possible to use the shale as an unconventional carbon storage reservoir (Nuttall and others, 2005). Fractures are the primary porosity in gas reservoirs and are preferentially oriented in northeast-southwest directions in the Big Sandy Gas Field of eastern Kentucky (Shumaker, 1987). The Big Sandy Gas Field is the state's largest gas field. Most of the gas in this field comes from the Cleveland and Lower Huron Members of the shale at an average depth of 3,200 ft. Gas is produced from fractured gas drive reservoirs (Boswell, 1996). A regional network of planar, high-angle joints within the Lower Huron appears to provide the permeability network for the shale (Kubick, 1993). The high organic content of the shale allows the possibility that carbon dioxide would adsorb onto the shale matrix, similarly to carbon storage mechanisms proposed for coal (Nuttall and others, 2005).

Overlying Sealing/Confining Units. The shale itself is a regional confining unit, with permeabilities generally below 0.1 md. In addition, the high organic content means that carbon would likely adsorb onto the

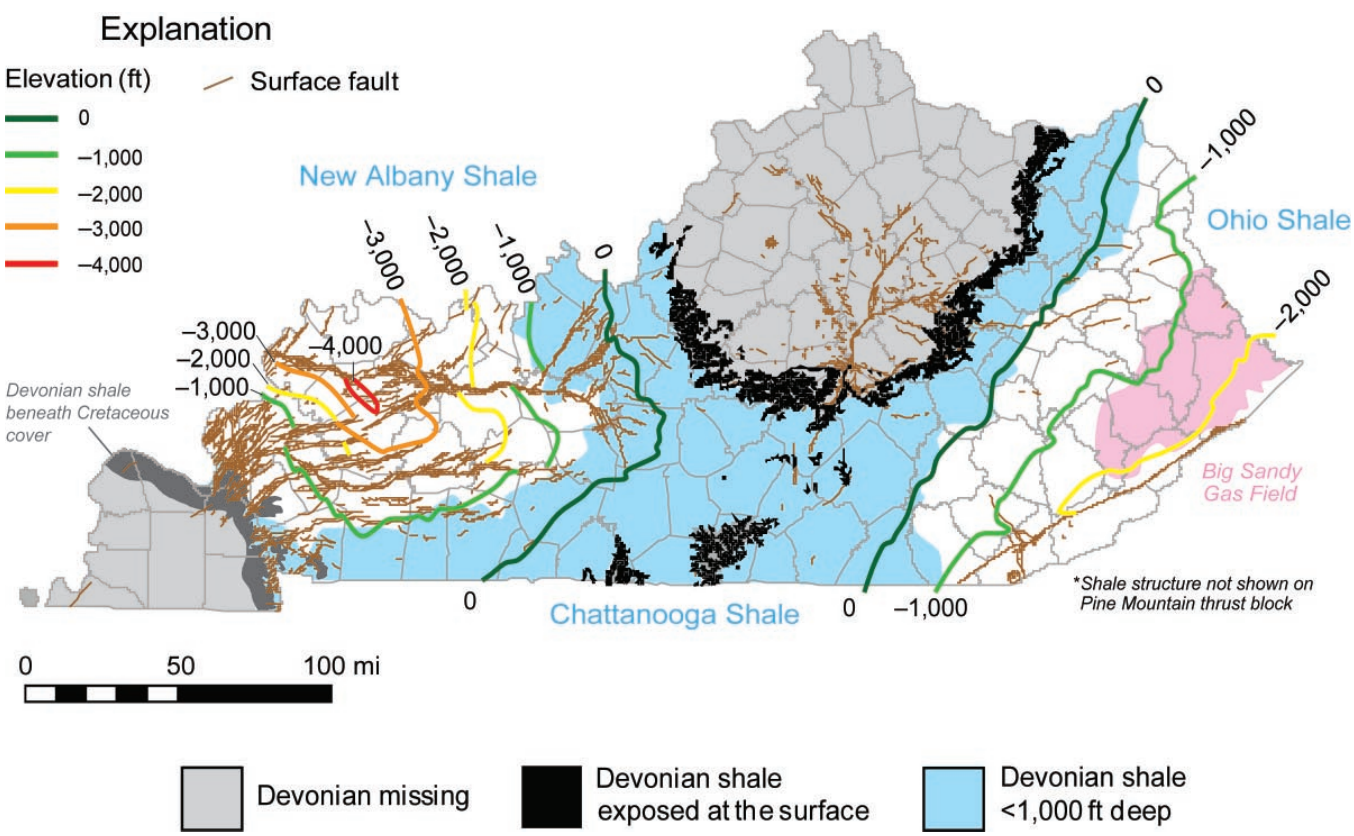

Figure 4.61. Structure on the Devonian shale interval. Well data are not shown. Datum is sea level.

shale matrix, increasing the sealing efficiency of this unit. Busch and others (2008) have demonstrated that CO_2 adsorption by shales enhances the effectiveness of shales as confining or sealing units. Many wells have been drilled into the shale, however, so there may be issues related to wellbores as potential pathways for leakage in large projects. In enhanced gas recovery projects, some wells would be used for injection, and others would be used for recovery.

CO_2 Storage Potential. The Devonian shale interval was investigated in this report as a seal or confining interval, but the shale has theoretically large potential storage capacity. The black shale is Kentucky's primary natural gas producer. Nuttall and others (2005) estimated that the shale has the capacity to store more than 28 billion short tons of CO_2. Phase II research by the DOE-sponsored Midwest Regional Carbon Sequestration Partnership, Midwest Geological Sequestration Consortium, and Southeast Regional Carbon Sequestration Partnership is investigating the shale as a seal, possible storage reservoir, and for using CO_2 for enhanced gas recovery in the shale. The concept of storage in a low-permeability (tight) shale is still theoretical. More testing is needed to see if CO_2 for enhanced gas recovery will work in Kentucky, as well as for determining if high rates of injection can be achieved for larger-scale sequestration.

Cross Sections

Most of Kentucky's major electricity-generating facilities are located along rivers because they require large amounts of water. Future fossil-fuel-powered electric facilities, coal-to-liquids plants, coal-to-gas plants, large ethanol plants, and other industrial plants that produce CO_2 are also likely to require water. Therefore, a series of cross sections was constructed across Kentucky's major waterways (Fig. 4.63). Cross sections show the stacking and correlation of subsurface rock units. Simplified cross sections are shown as page-size figures in this section, and larger detailed sections including geophysical log profiles are in separate plates. Descriptions and pertinent background information for units shown in the cross sections can be found in the "Rock Unit Summary" section of this

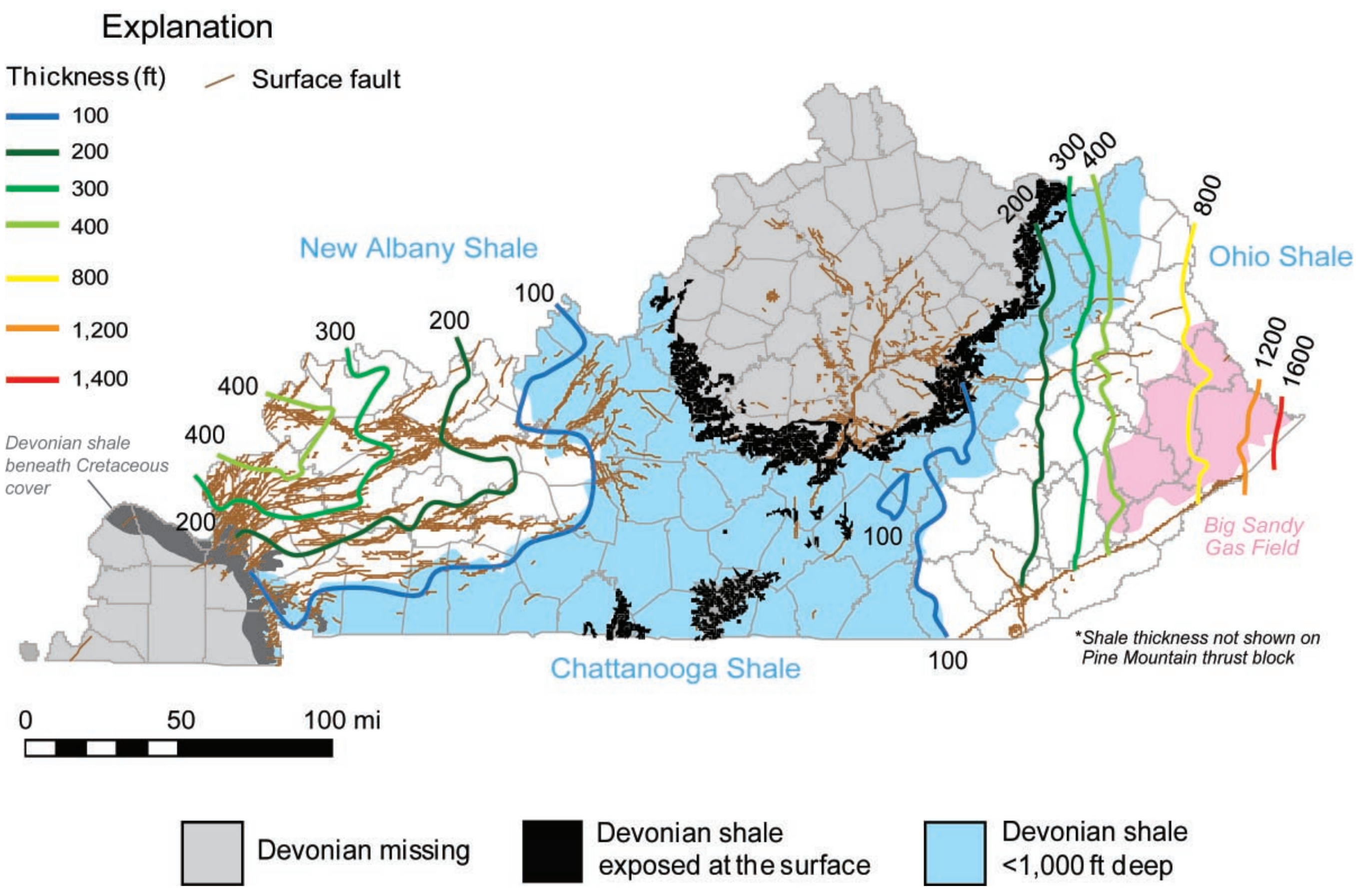

Figure 4.62. Thickness of the Devonian shale interval in Kentucky. Note change in scale in eastern Kentucky to account for eastward thickening of the interval. Well data are not shown.

chapter. The descriptions of the cross sections are not site reports, but should help operators of existing plants visualize and better understand the possible reservoirs and seals beneath their plants, and the depths at which those units occur. The cross sections should also provide developers and planners with data that will aid in evaluating the carbon storage and other underground injection possibilities for future industrial sites.

Units shown on the small-scale river cross sections and in the oversized plates correspond to the intervals described in the preceding "Rock Unit Summary." Units are color-coded below depths of approximately 2,500 ft in the figures (but not the plates). Color codes correspond to interval descriptions as potential reservoirs, confining intervals, etc., as shown in Figure 4.5 in the "Introduction" section of this chapter. The 2,500-ft depth is the approximate depth at which injected CO_2 would be at supercritical conditions. The interval thickness shown in the figures and plates is not a reservoir thickness; potential reservoirs within an interval would occupy only small parts of the interval shown. Each page-size river cross section in this chapter has a corresponding oversize plate. The plates show traces of the downhole geophysical logs used to make the correlations. Gamma-ray profiles are color-coded on the plates to aid visualization of the correlations.

For each cross section, information is provided about its geographic location and the major cities and existing fossil-fuel-powered electricity-generating facilities along that section (non-CO_2-producing plants are not shown), the geophysical logs used to make the section and maps of additional nearby data, known geologic structures and dip along section, and subsurface geologic units (from the bottom up), with details from logs where pertinent to carbon storage. A brief summary of the section is also provided.

Ohio River (West)

The Ohio River cross section is divided into four sections. The westernmost section extends from just north of Ballard County to the Henderson-Evansville area (Figs. 4.63–4.64). Henderson and Paducah are two large towns along this part of the river. Fossil-fuel-pow-

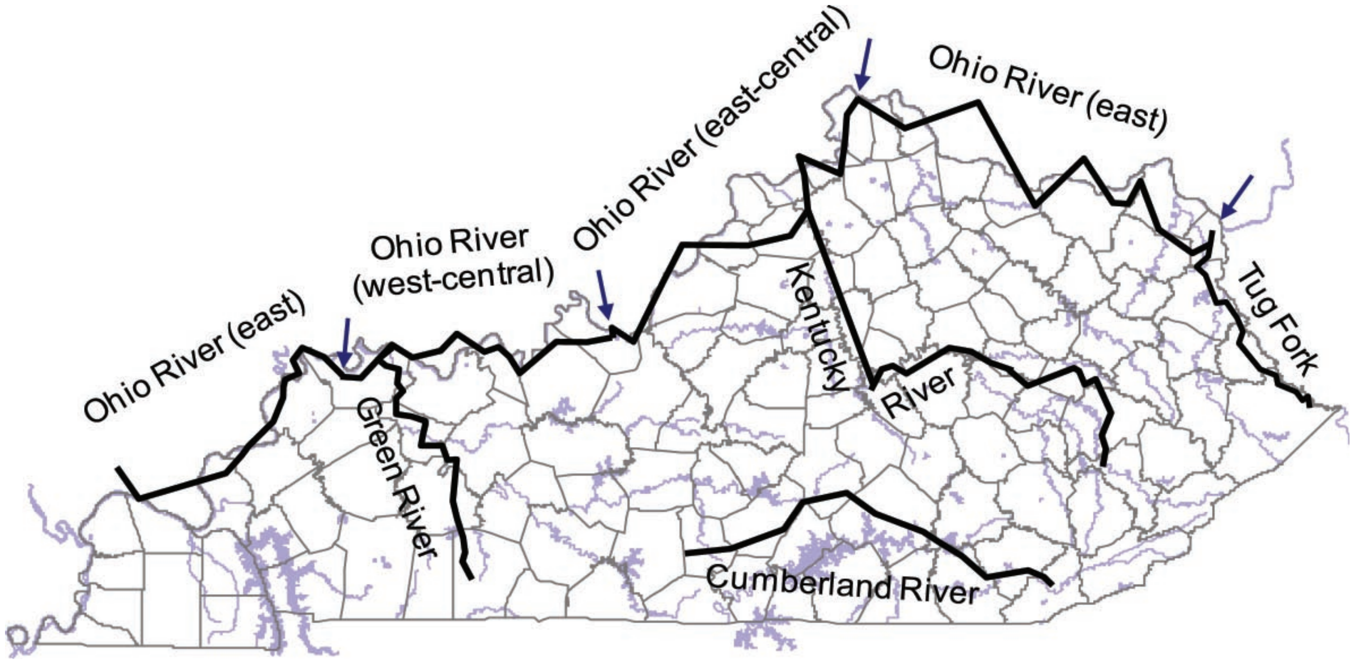

Figure 4.63. Locations of cross sections discussed in this report.

ered electricity-generating facilities on the Kentucky side of the river in this area are listed in Table 4.10. An additional coal- and natural gas-fired power station is located on the Illinois side of the river. In addition to the existing plants, Enviropower's Kentucky Western Power (500 MW) is proposed for Marshall County.

The Ohio River (west) section was constructed from data from 15 wells, one of which is in Illinois (Figs. 4.64–4.65, Table 4.11, Plate 4.1). The Texas Pacific Oil No. 1 Farley well in Illinois is the deepest well and reaches the Mount Simon. All of the other wells are significantly less deep; four wells penetrate at least the top of the Knox. Drillers' descriptions of cuttings are available for the Texas Oil No. 1 Farley (Illinois) and the Shell Oil No. 1 Davis wells. The Shell-Davis well is depicted in a cross section along the Rough Creek Fault System by Noger and Drahovzal (2005), which is a useful complement to the cross section provided herein.

Seismic Risk. The Ohio River (west) section is within the New Madrid Seismic Zone. Earthquakes in this zone are generated from faults in a deep-seated graben beneath the Mississippi River Valley south of the Ohio River. Seismic risk is one of the geologic issues for future industrial and electric-plant construction and carbon storage along this part of the river. The proposal and guidelines for the FutureGen project (2005-2006), a federally funded power plant of the future with carbon storage, had requirements for minimal seismic risk. For the FutureGen proposal, planned sites were required to be located in areas with estimated peak ground acceleration of less than 30 percent g at 2 percent chance of being exceeded in 50 years, based on the U.S. Geological Survey's seismic hazard/risk assessment. Along the Ohio River, the highest potential ground acceleration is estimated to be on the western end of the section (more than 80 percent g) and decreases eastward to 30 to 35 percent g in the vicinity of Henderson (Fig. 4.66). Wang and others (2007) used recent seismic data from the Kentucky Department of Transportation to recalculate the estimated peak ground acceleration for Henderson, and determined a peak ground acceleration of 20 percent g with 2 percent chance of being exceeded in 50 years. Although the estimated ground acceleration is lower than the U.S. Geological Survey's estimates by 10 to 15 percent, a westward increase in ground acceleration would still be expected and would still likely exceed 30 percent g along much of the Ohio River (west) section west of Henderson. Seismic-risk analysis is required for EPA underground injection control permits and would have to be considered in any future large-scale carbon-storage project. Likewise, if federal funding is to be sought for any part of the project, it is likely that a seismic-risk assessment will be needed and that at least the western parts of this cross

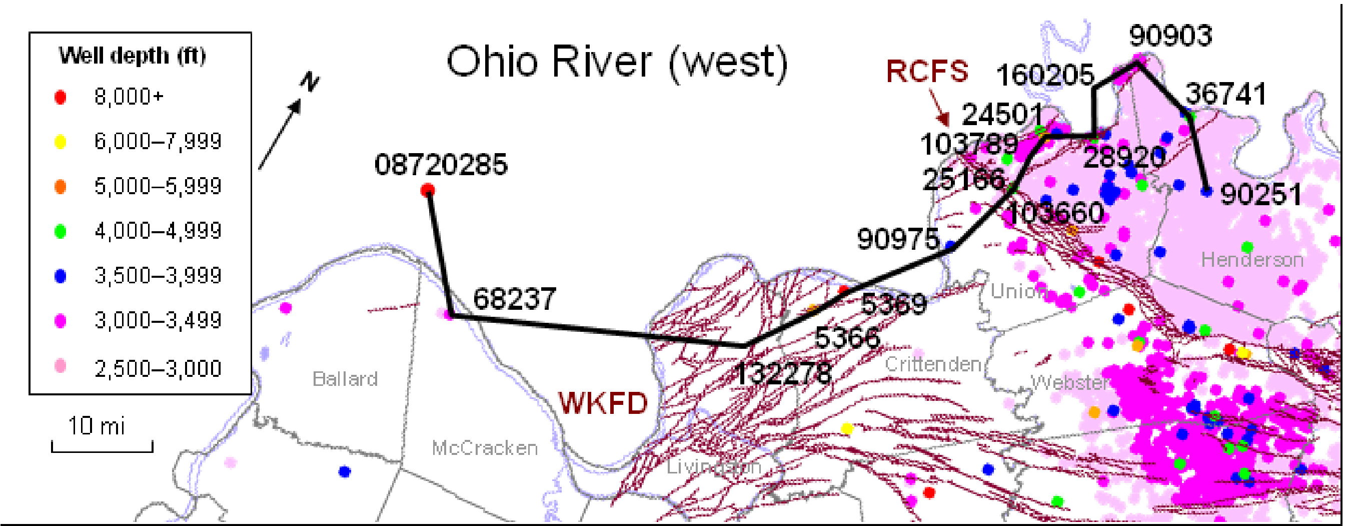

Figure 4.64. Location of the Ohio River (west) cross section. Wells used in the section are labeled by their record number (see Table 4.2). Locations of other wells in the vicinity are color-coded for depth. Wells less than 2,500 ft in depth are not shown. Faults exposed at the surface are shown as brown lines. FD = Western Kentucky Fluorspar District faults. These faults are only shown where they occur at the surface. The faults continue beneath Cretaceous cover in the counties to the west. Map is oriented to better fit on the page. RCF = Rough Creek Fault System.

Table 4.10. Electric-power-generating stations along the Kentucky side of the western part of the Ohio River. Data from Kentucky Public Service Commission (June 10, 2008) and Energy Information Administration (2006).

Owner	*Plant Name*	*Capacity (MW)*	*Fuel*	*County*
Tennessee Valley Authority	Shawnee	1,750	coal	McCracken
Air Products and Chemicals Inc.	Calvert City	26.7	natural gas	Marshall
Cinergy Solutions O&M LLC	Marshall Energy	688 (inactive)	natural gas, fuel oil	Marshall

section will exceed limits for estimated ground acceleration.

Structure and Faulting. The dip of subsurface strata along this stretch of the river (Fig. 4.65, Plate 4.1) is complicated by many faults. Faults are covered by Cretaceous and younger sediment at the surface along parts of the river in Ballard and McCracken Counties, but are known to continue beneath the surface cover. Most faults are oriented northeast-southwest with a spacing of 2 to 3 mi between faults. Several faults splinter into complex bifurcating structures with even closer spacing. Most of these faults are not active, so they do not pose a seismic risk. Based on the FutureGen proposal evaluations and current EPA review of phase II demonstration projects for the U.S. Department of Energy's regional carbon sequestration partnerships, however, any fault that intersects the area of a potential injection plume would need to be evaluated for its potential to act as a plane of leakage from the reservoir to shallower horizons or the surface. Many faults are sealing, and actually improve the ability of a subsurface reservoir to hold liquids and gases by creating physical barriers or folds. Others may be pathways for leakage. Such evaluations are site-specific and are beyond the scope of this report.

Precambrian Basement. Precambrian strata have not been penetrated along this part of the river, so interpretations of depth to basement are based on interpretations of seismic data. Complex faulting of the basement south and west of Union County results in variable depths to basement along the westernmost part of this section. South of the Rough Creek faults in southern Union County, the depth to basement is estimated at more than 21,000 ft (see "Rock Unit Summary"), although depths of 25,000 ft occur just east of the line of section in Webster County (Noger and Drahovzal, 2005). North of the faults, the depth to basement is approximately 14,000 ft in western Union County and decreases eastward.

Mount Simon Sandstone. The Mount Simon Sandstone is only penetrated in the Texas Pacific Oil No. 1

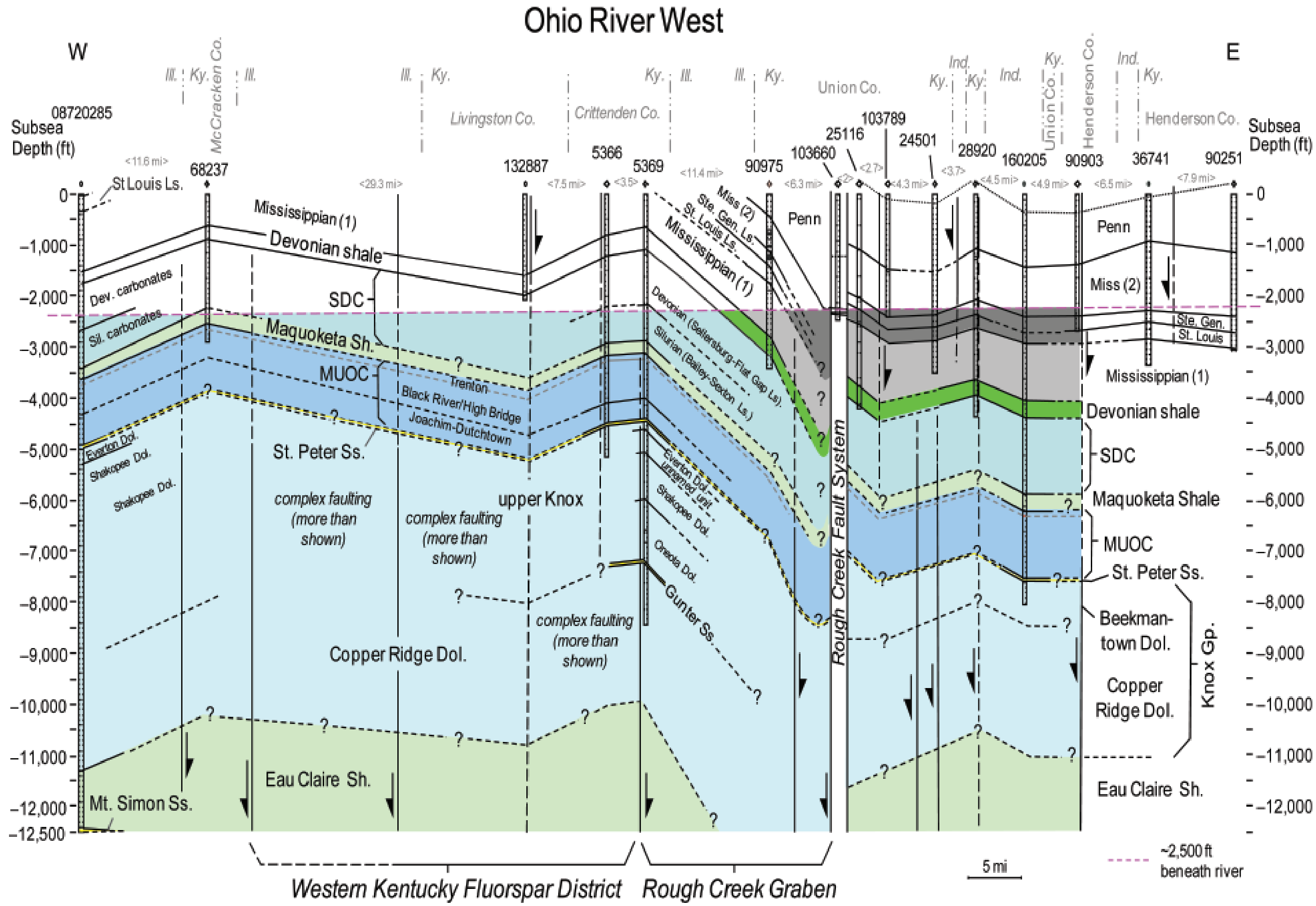

Figure 4.65. Ohio River (west) cross section showing rock-unit intervals discussed in the “Rock Unit Summary.” Intervals are color coded according to their generalized carbon storage category as shown in Figure 4.5. Location of the section is shown in Figure 4.64. Wells used in this cross section are listed in Table 4.11. Expanded cross section with geophysical logs is Plate 4.1. Faults that can be mapped at the surface are shown as solid at the top and dashed downward on the cross section. Faults that are not visible on the surface, but have been detected at depth from seismic analyses, are shown as solid at the bottom and dashed upward in the cross section. Basement depths are based on preliminary seismic analyses and subject to change. Surface faults connect to basement faults, but the level at which they connect or split is uncertain without specific data for that location. In some areas, faulting is too complex to be shown. Also, because of the uncertainty of offset with depth along faults, correlations are shown between wells without offset along faults, except across the Rough Creek Fault System, in order to show the general or average dip of beds. Miss (1)=lower part of the Mississippian from the Salem Limestone to the New Providence Shale, Miss (2)=upper part of the Mississippian from the base of the Pennsylvanian (Penn) to the top of the Ste. Genevieve Limestone, MUOC=Middle–Upper Ordovician carbonate interval, Penn=Pennsylvanian strata, SDC=Silurian–Devonian carbonate interval.

Table 4.11. Information on wells used for the Ohio River (west) cross section. Record numbers can be used to view well data in the KGS Oil and Gas Database.

Permit	*Record No.*	*Well Name*	*County*	*Elevation (ft)*	*Total Depth (ft)*	*Formation at TD*	*Samples*
	1208720285	Texas Pacific Oil 1 Farley	Johnson, Ill.	594	14,284	Mount Simon Sandstone (Cambrian)	
72216	68237	McCracken Explor. 2 Gibbs	McCracken	348	3,260	Maquoketa Shale (Ordovician)	
100776	132278	Chesapeake Appalachia 826228 Workman	Livingston	588	2,666	upper Knox Group (Ordovician)	
33498	5366	Ecus Corp. 1 Shaffer	Crittenden	482	5,657	upper Knox Group (Ordovician)	X
6952WF		Shell Oil 1 Davis	Crittenden	363	8,821	upper Knox Group (Ordovician)	X
78442	90975	Equitable K10005 Heine Bros.	Union	351	3,773	upper Corniferous (Devonian)	
	103660	Yingling 1 Adamson	Union	374	2,841	Glen Dean Limestone (Mississippian)	
1963WF	25116	Sun Oil 3 Robertson	Union	390	4,599	middle part of Devonian	X
	103789	Superior Oil 1 Conway	Union	399	2,812	Renault Limestone (Mi)	
36358	24501	Quasar Inc. 1 Burlinson-Gough	Union	405	3,910	St. Louis Limestone (Mississippian)	X
7527	28920	Sun Oil 1 Biggs	Union	341	4,710	undifferentiated Silurian	X
51367	160205	Kestrel Resources 1 Hasting	Posey, Ind.	367	8,429	upper Knox Group (Ordovician)	
	90903	Ellis 1 Ellis	Henderson	360	3,062	Ste. Genevieve Limestone (Mississippian)	
58209	36741	Hargrove 1 Dorsey	Henderson	356	3,719	Salem-Warsaw Limestone (Mississippian)	
32735	90251	Turner 1 Pritchett	Henderson	430	3,500	Warsaw Limestone (Mississippian)	X

Farley well in southern Illinois along this part of the river, where the sandstone is 660 ft thick at a depth of 13,060 ft (Fig. 4.65, Plate 4.1). Regional thickness trends suggest that it likely thins eastward as it shallows, and it may be missing in some areas along this section (see “Rock Unit Summary”). Preliminary seismic analysis based on the sandstone’s position above Precambrian basement indicates that where it does occur along this stretch of the river, it is below the optimal depth (7,000 ft) for likely porosity development inferred by Hoholick and others (1984).

Eau Claire Formation. The Eau Claire is only penetrated in the Texas Pacific Oil No. 1 Farley well in southern Illinois along this part of the river, where it is 2,166 ft thick, at a depth of 11,894 ft (Fig. 4.65, Plate 4.1). Based on seismic analysis, it varies from 10,000 to more than 14,000 ft deep along the section.

Lower Knox–Copper Ridge Dolomite. The Copper Ridge is only penetrated in the Texas Pacific No. 1 Farley and Shell Oil No. 1 Davis wells, so its depth and thickness in this area are largely estimated from regional stratigraphic and seismic analyses. In the Texas Pacific well, the Copper Ridge (equals Potosi in Illinois) is 1,470 ft thick and the top of the formation is 10,430 ft deep. Eastward along the section, the unit generally shallows (with significant rise and fall between faults) to depths of 7,345 to 7,545 ft on the south side of the Rough Creek Graben in the Shell Oil Da-

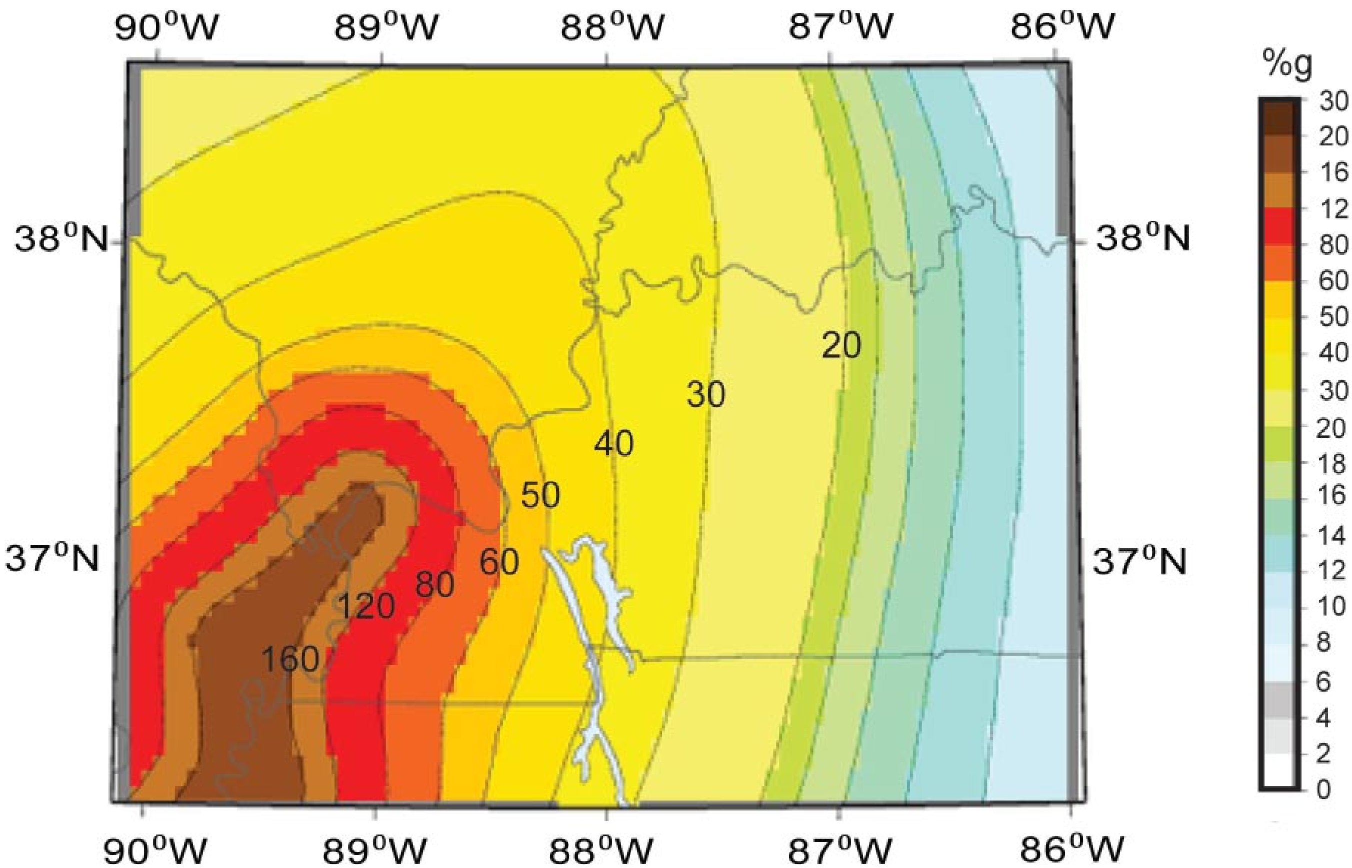

Figure 4.66. Peak ground acceleration at 2 percent chance of being exceeded in 50 yr (data from U.S. Geological Survey custom hazards map Web site, geohazards.usgs.gov/hazards/apps/cmaps/).

vis well (see discussion of Gunter Sandstone below). Based on data from east of the line of section, the top of the Copper Ridge might deepen to more than 9,500 ft just south of the Rough Creek faults (Noger and Drahovzal, 2005). North of the faults, the Copper Ridge is 7,000 to 8,000 ft beneath the surface in the Henderson-Evansville area (Fig. 4.65, Plate 4.1).

Because few wells penetrate the Copper Ridge along this stretch of the river, it is difficult to assess the extent of any porosity development in the interval. The Shell Oil No. 1 well encountered saline water at a depth of 6,068 to 7,700 ft (1,253 to 2,884 ft from the top of the Knox) and at 7,978 ft (3,162 ft from the top of the Knox). The shallower zone, which is likely in the lower Beekmantown and upper Copper Ridge, produced 0.25 to 34 barrels/min (97,000 ppm chlorides). The deeper zone (in the Copper Ridge) encountered 64 barrels/min of saline water (130,000 ppm chloride). Dolomitic siltstones with minor porosity were noted in the shallower zone from 7,490 to 7,545, 7,575 to 7,595, and 7,700 to 7,730 ft depth.

Gunter (Rose Run Equivalent) Sandstone. Sample descriptions from the Shell Oil No. 1 Davis well indicate four dolomitic sandstones from 7,305 to 7,345 ft (40 ft thick), 7,490 to 7,545 ft (55 ft thick), 7,575 to 7,595 ft (20 ft thick), and 7,700 to 7,730 ft (30 ft thick). One of these sandstones (or more) is likely the Gunter Sandstone of Missouri and southern Illinois. The Gunter caps the Copper Ridge, similarly to the Rose Run Sandstone in eastern Kentucky. In this well, the base of the Gunter (and therefore the top of the Copper Ridge) could be placed at the base of any of the four sandstones. For the purpose of carbon storage, however, the sandstone from 7,490 to 7,545 ft has porosity and is considered the base of the Gunter for this report (Fig. 4.65, Plate 4.1). Porosity is indicated on the neutron log from 7,500 to 7,525 ft. The uppermost and lowermost two sandstones have only narrow porosity zones. The resistivity curve also shows low resistivity (and possible porosity) from 7,505 to 7,507 ft and 7,512 to 7,530 ft. These sandstones are very fine- to medium-grained, white to yellow (stained), cherty, and described as “incoherent” in the sample descriptions;

the meaning of "incoherent" is uncertain, but could mean unconsolidated or friable. The four sandstone intervals in the Shell Oil Davis well are separated by silty and cherty, nonporous dolomite. The Gunter likely occurs beneath much of this stretch of the river, although the fact that multiple sands are separated by dolomites in the Shell well could indicate interfingering between the sandstones and dolomites, and potential lateral facies changes from sandstone to sandy (low-porosity) dolomite.

Upper Knox (Everton-Beekmantown). The upper Knox is penetrated in five wells along this section (Fig. 4.65, Plate 4.1). Westward along this section, the Beekmantown (equals Shakopee and Oneota Dolomites of southern Illinois and Missouri) is overlain by the Everton Dolomite, which is also part of the Knox Group. The top of the Knox on the eastern end of the section is the top of the Beekmantown or Shakopee Dolomite. The top of the Knox on the western end of the section is the top of the Everton Dolomite. The unconformity at the top of the Knox truncates the Everton eastward.

The top of the Knox is at a depth of 4,500 to 5,500 ft in the western part of the section. In the Shell Oil Davis well, on the south side of the Rough Creek Graben, the top of the Knox (Everton) is at a depth of 4,816 ft. Within the graben, just south of the Rough Creek faults, the top of the Knox may be more than 7,500 ft deep (Noger and Drahovzal, 2005).

Detailed sample descriptions for the upper Knox are provided in the Shell No. 1 Davis well. In that well, 40 barrels/hr of salty (54,000 ppm chloride) and sulfurous water were encountered at a depth of 5,498 ft, which is 682 ft from the top of the Knox, and may represent a fracture. A minor porosity zone is also at a depth of 4,816 ft in a dolomitic siltstone to sandy dolomite at depths of 4,930 to 4,935 ft, 114 to 119 ft beneath the unconformity at the top of the Knox. In the nearby Ecus Corp. No. 1 well, a sandy dolomite at 5,200 ft (140 ft beneath the top of the Knox) may be an equivalent horizon. Therefore, there is a possibility of a thin, low-porosity zone in the upper Knox that can be correlated between wells along this stretch of the river. How continuous these and other narrow porosity zones in the upper Knox might be is uncertain because of a lack of deep wells away from the fault system.

St. Peter Sandstone. The St. Peter is penetrated in five wells along this section (Fig. 4.65, Plate 4.1), and is likely continuous between wells. It is 75 ft thick in the Texas Pacific No. 1 Farley well (top of formation at 5,513 ft) and is 71 ft thick in the Shell Oil No. 1 Davis well (top of formation at 4,745 ft). The sandstone is described as dolomitic, however, and neutron logs show little evidence of porosity. Sandy carbonates were also found in the overlying Dutchtown Formation (part of the Middle-Upper Ordovician carbonate interval) in the Shell Oil No. 1 Davis well, but they were found to have little porosity after coring.

Middle-Upper Ordovician Carbonates. The Middle-Upper Ordovician carbonates are penetrated in five wells along this section (Fig. 4.65, Plate 4.1), and show little evidence of porosity. Sandy carbonates were cored in the Shell Oil No. 1 well (4,500 to 4,530 ft) from the lower part of this interval in the Dutchtown Formation (245 ft above the St. Peter Sandstone), but had no porosity. Descriptions and well testing results are included in the driller's reports. There is very little oil and gas production or evidence of significant porosity in the Middle-Upper Ordovician carbonates in western Kentucky, or for that matter the southern part of the Illinois Basin (see Seyler and Cluff, 1991).

Upper Ordovician Shale. The Maquoketa Formation is penetrated in five wells along this section (Fig. 4.65, Plate 4.1). The unit is shale-dominated, 220 to 255 ft thick, and 2,400 to 7,000 ft deep. Where the Maquoketa is unfaulted, it would likely provide an adequate seal to underlying injection. The unit is more than 2,500 ft deep along almost the entire cross section (except for a single fault block), which would be the approximate minimum depth required for confining intervals to keep any CO_2 injected into underlying units in a supercritical state.

Silurian-Devonian Carbonates and Sandstones. The Silurian-Devonian carbonates are penetrated in five wells along this section (Fig. 4.65, Plate 4.1). No porosity or saline water were noted in this interval along this section. In fact, there has been very little oil and gas production or evidence of significant porosity in Silurian-Devonian carbonates at depth in western Kentucky, or for that matter the southern part of the Illinois Basin (see, for example, Seyler and Cluff, 1991).

Devonian Shale. The New Albany Shale is penetrated in nine wells along this section (Fig. 4.65, Plate 4.1), and is considered continuous between wells. The top of the New Albany is near the subcrop of the shale beneath Cretaceous strata in Ballard County. On the south side of the Rough Creek Graben, in Crittenden

County, the top of the shale is approximately 1,000 ft deep in the Shell Oil Davis well. Within the graben, in southern Union County, the shale may deepen to more than 4,000 ft (Noger and Drahovzal, 2005). North of the Rough Creek faults, the shale varies from 3,800 to 4,700 ft in depth.

Along this stretch of the river, the shale is 200 to 450 ft thick. It is thickest in the Rough Creek Graben and generally thins west and north out of the graben (Schwalb and Potter, 1978). No gas has been produced from the shale in this part of the basin, so the use of CO_2 for enhanced gas production would be limited. Only along the parts of the river where the New Albany is more than approximately 2,500 ft deep could it be used as a confining interval to keep any CO_2 injected into underlying units in a supercritical state.

Shallower Porosity Horizons Deeper than 2,500 ft. Several Mississippian formations are conventional oil and gas targets in this part of the basin, and occur at depths of more than 2,500 ft along part of this section (Fig. 4.65, Plate 4.1). These units are not discussed in the "Rock Unit Summary" because they were shallower than the Devonian shale, but they may offer small-scale injection possibilities or enhanced oil and gas opportunities. Summaries for known Mississippian porosity (oil and gas production) include field studies and overviews in Miller (1968), Zupann and Keith (1988), and Leighton and others (1991), as well as many Kentucky Geological Survey pool and field studies. Several fields along this part of the Ohio River are discussed in chapter 2 of this report.

The shallowest horizon at depths of more than 2,500 ft that might contain local porosity is the Upper Mississippian Tar Springs Sandstone (part of the Mississippian (2) interval in Figure 4.65) in the Yingling No. 1 Adamson well. This well is just south of the Rough Creek Fault System.

The Mississippian Ste. Genevieve Limestone is nearly 2,500 ft in depth from the deeper part of the Rough Creek Graben north into Henderson County. The McCloskey reservoirs (drillers' term) of the Ste. Genevieve had shows of oil from 2,688 to 2,722 ft (34 ft) in the Hargrove No. 1 Dorsey well and from 2,899 to 2,952 ft (53 ft thick), 2,912 to 2,942 ft (20 ft thick), and 2,989 to 3,000 ft (11 ft thick) in the Quasar No. 1 Burlinson-Guogh well. Drillstem tests were performed in both wells. McCloskey reservoirs were deposited as oolitic carbonate-shoal deposits. Hence, reservoirs are typically localized and elongate. Production is from stratigraphic traps or combined stratigraphic-structural traps. McClosky reservoirs have produced nearly 20 percent of Mississippian petroleum in the Illinois Basin (Cluff and Lineback, 1981).

The Mississippian Salem and Warsaw Limestones are more than 2,500 ft deep where the Ste. Genevieve Limestone is more than 2,500 ft deep (part of Mississippian (1) in Figure 4.65). The Salem had shows of oil in the Hargrove well at a depth of 3,363 to 3,390 ft (27 ft thick), the Quasar well at 3,287 to 3,291 ft (4 ft thick), and at depths of 3,361 to 3,363 ft (2 ft thick) and 3,432 to 3,439 ft (7 ft thick) in the Sun Oil No. 3 Robertson well, Union County. Mississippian horizons are common targets for oil and gas in this part of the basin, and there are numerous oil and gas fields in Mississippian reservoirs in Union and Henderson Counties. The density of penetrations in some areas may limit large-scale carbon storage in many of these reservoirs, because old, unplugged, or poorly cemented wellbores are potential sources of leakage to the surface.

Coals Deeper than 1,000 ft. In Union County, just south of the Rough Creek Fault System, Pennsylvanian strata are deeper than elsewhere in the basin, and coals in the Tradewater and Carbondale Formations are more than 1,000 ft deep. In the Yingling Adamson well, the Springfield (W. Ky. No. 9) coal, which is the most productive seam in the basin, is more than 1,000 ft deep. Coalbed methane is not currently produced from these beds, although the area south of the Rough Creek Fault System (and in the fault system) are areas of potential interest for possible coalbed methane resources in western Kentucky. Tests are currently ongoing in DOE-sponsored projects for coal sequestration and for enhanced coalbed-methane recovery with carbon dioxide. The Midwest Geological Sequestration Consortium has injected small amounts of CO_2 into the Springfield (W. Ky. No. 9) coal bed in Illinois to test coal sequestration in the basin. Most of the coal sequestration projects in the nation are focused on enhanced coalbed methane recovery in existing coalbed methane fields, rather than for large-scale sequestration in areas without commercial coalbed methane production. Whether sequestration in coals would be economic outside of existing commercial coalbed-methane fields is uncertain, but research continues.

Ohio River (West) Summary. The westernmost part of the Ohio River is in the New Madrid Seismic Zone. There is also a high concentration of faults (not related to seismic hazard) that would have to be investigated to determine if they are sealing or pathways for leakage prior to any large-scale injection project. The Mount Simon Sandstone is likely too deep for carbon storage, and the St. Peter Sandstone has low porosity and permeability where it has been encountered. There may be possibilities for carbon storage in the Knox Group, but there are too few wells in this area to indicate if porosity zones noted in the few wells that penetrate the Beekmantown and Copper Ridge are laterally extensive. Use of the Knox for large-scale storage would likely require stacking of multiple porosity zones or openhole completions within the Knox in order to develop cumulative capacity from many thin, discrete porosity intervals. Mississippian strata offer possibilities where they occur at more than 2,500-ft depth in Henderson and Union Counties, but are targets of oil and gas exploration and locally may have many existing well penetrations that would have to be considered as potential pathways for leakage in any injection project.

The area north of (and in) the Rough Creek Fault System includes some of the most productive oil and gas fields in western Kentucky, including Uniontown Consolidated, Powells Lake Consolidated, and Smith Mills North. Nearby fields with cumulative production in excess of 5 million barrels include Morganfield South, Hitesville Consolidated, and Smith Mills in Kentucky; Inman East Consolidated in Indiana and Illinois; and Mount Vernon Consolidated, Caborn Consolidated, and Heusler Consolidated in Indiana (Brownfield, 1968). Several of these fields are discussed in chapter 2 of this report. Production from these fields is shallower than 2,500 ft. In the future, when CO_2 is available for much less than its current price, it might be used to repressurize old fields or for small-scale enhanced oil and gas recovery, but these fields would not be suitable for large-volume storage in tandem with enhanced oil and gas recovery because of their shallow depth.

Ohio River (West-Central)

The Ohio River (west-central) section extends from the Henderson-Evansville area to approximately the Meade-Hardin County line in Kentucky (Figs. 4.63, 4.67). Fossil-fuel-powered electricity-generating facilities along the Kentucky side of this stretch of the river are listed in Table 4.12. Two additional fossil-fuel-powered power stations are located on the Indiana side of the river.

The Ohio River (west-central) section was constructed with data from 14 wells, two of which are in Indiana (Fig. 4.67, Plate 4.2, Table 4.13). Because of the dip of strata, older units are penetrated on the eastern end of the section. The deepest wells on the western end of the section only penetrate into Mississippian strata. Drillers' descriptions of cuttings are available for the Zogg Oil No. 1 Yunker-Hart well. A cross section by Noger and Drahovzal (2005) is oriented subparallel to this section along the Rough Creek Fault System (RCF in Figure 4.63), approximately 20 mi south of the

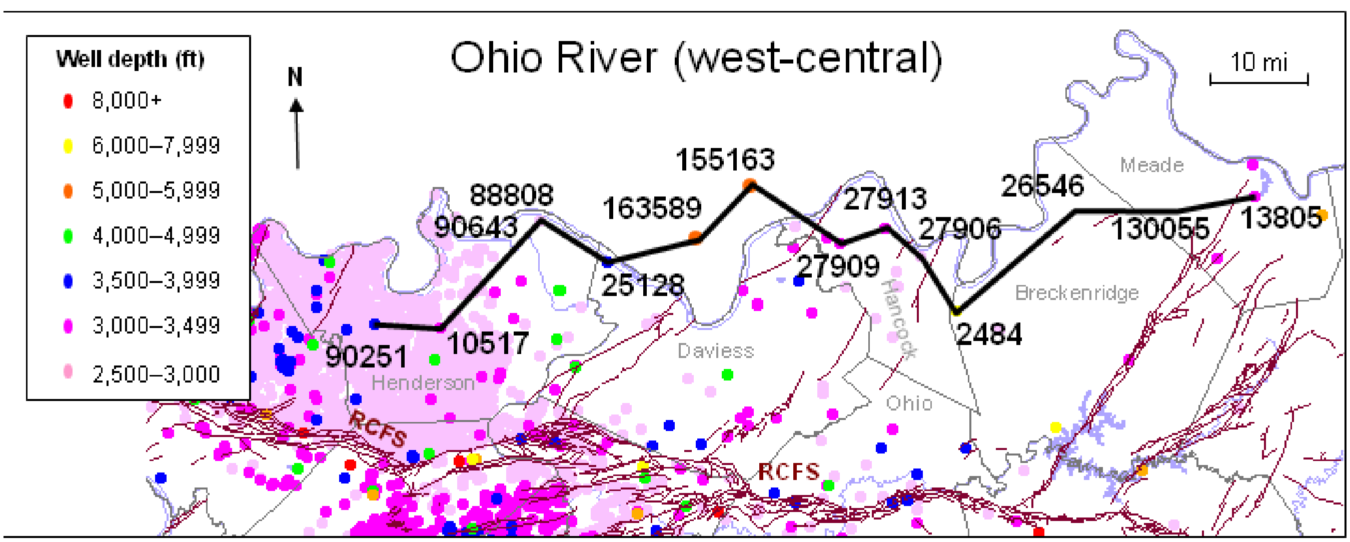

Figure 4.67. Location of the Ohio River (west-central) cross section. Wells used in the section are labeled by their record number (see Table 4.13). Locations of other wells in the vicinity are color-coded for depth. Wells less than 2,500 ft in depth are not shown. Faults exposed at the surface are shown as brown lines. RCF=Rough Creek Fault System.

Table 4.12. Electric-power-generating stations along the Kentucky side of the west-central part of the Ohio River. Data from Kentucky Public Service Commission (June 10, 2008) and Energy Information Administration (2006).

Owner	*Plant Name*	*Capacity (MW)*	*Fuel*	*County*
Henderson Municipal Power and Light	Henderson 1	44	coal	Henderson
Henderson Municipal Power and Light	Henderson 1	2	fuel oil, natural gas	Henderson
Owensboro Municipal Utilities	E. Smith	445	coal	Daviess
Western Kentucky Energy/Big Rivers	Coleman	521	coal	Hancock

Ohio River, and may provide additional data for groups interested in this region.

Structure and Faulting. Strata along this part of the river exhibit a shallow westward dip (Figs. 4.67–4.68, Plate 4.2). One northeast–southwest-oriented graben (with bounding faults) intersects the line of section in Hancock County. A second series of northeast–southwest-oriented faults and grabens terminates at the surface south of the river in Meade County along the western edge of the section.

Precambrian Basement. Precambrian strata have not been penetrated along this part of the river, so interpretations of depth to basement are based on seismic data, which are currently being evaluated at the Kentucky Geological Survey, and may be subject to change in the future for this area. Basement rocks are shallowest on the western end of this part of the river and shallow eastward. Basement is interpreted to occur at depths of more than 12,000 ft in Henderson County on the western end of the section and depths of less than 6,000 ft on the eastern end of the section in Meade County (Fig. 4.68, Plate 4.2).

Mount Simon Sandstone. The Mount Simon has not been penetrated along this part of the river so interpretations of depth and thickness must be inferred from seismic data (see “Rock Unit Summary”). The Mount Simon is interpreted to be 400 to 800 ft thick, although it thins rapidly south from the river. It is likely thickest in northern Meade County. The depth to the top of the Mount Simon decreases from approximately 12,000 ft in Henderson County to 5,500 ft in Meade County (Fig. 4.68, Plate 4.2). Only in the eastern part of the section is the Mount Simon at depths of less than 7,000 ft, where it has a greater likelihood of exhibiting porosity. The Kentucky Geological Survey No. 1 Marvin Blan well, Hancock County, was drilled in the summer of 2009 by the Kentucky Consortium for Carbon Storage as part of the House Bill 1 initiative. Prior to drilling, seismic data were collected in Hancock County, and analysis of the data indicated that the Mount Simon was absent (or at least thinner than detectable by seismic data) near the well site. Subsequent drilling substantiated the analysis.

Eau Claire Formation. The Eau Claire has only been penetrated in the recently drilled Kentucky Geological Survey No. 1 Marvin Blan well, Hancock County, along this part of the river. In the Blan well, the Eau Claire was 187 ft thick at a depth of 7,387 ft and consisted of glauconitic and micaceous shales, fine-grained sandstone, and microcrystalline dolomite (Bowersox and Williams, 2009).

Based on seismic analysis, the Eau Claire shallows from more than 10,000 to 5,100 ft deep along the section. The formation was thinner than expected in the Blan well, but still more than 150 ft thick. Thickness variation is likely along this section. Where the unit is unfaulted, thick, and shale-dominated, it would likely provide an adequate seal to underlying injection in the Mount Simon, where the Mount Simon is present. The Eau Claire is more than 2,500 ft deep everywhere along this part of the river, so it could be used as a confining interval that would keep any CO_2 injected into the Mount Simon in a supercritical state.

Lower Knox–Copper Ridge Dolomite. The Copper Ridge is penetrated in three wells toward the eastern part of this cross section, where this interval is shallower (Fig. 4.68, Plate 4.2). It could be more than 9,500 ft deep on the western end of the section. The Gunter Sandstone that caps the Copper Ridge to the west may be absent along some parts of the section, which makes picking the top of the Copper Ridge difficult in this area. Based on regional stratigraphic analysis, the Copper Ridge is interpreted to be 1,500 to 2,500 ft thick, likely thickening to the west, and perhaps thickening within the northeast–southwest-oriented graben in Hancock County. The Copper Ridge was one of the targets of the Kentucky Geological Survey

Table 4.13. Information on wells used for the Ohio River (west-central) cross section. Record numbers can be used to view well data in the KGS Oil and Gas Database. The Kentucky Geological Survey No. 1 Marvin Blan well was drilled to basement in Hancock County after the completion of this report. It is located between the Zogg Oil No. 1 and Langford Oil No. 1 wells.

Permit No.	*Record No.*	*Well Name*	*County*	*Elevation (ft)*	*Total Depth (ft)*	*Formation at Total Depth*	*Samples*
32735	90251	Turner 1 Pritchett	Henderson	430	3,500	Warsaw Formation (Mississippian)	X
38325	10517	Hoffman 1 McCormick-Hodge	Henderson	382	3,240	Warsaw Formation (Mississippian)	X
	90643	Cherry & Kidd 1 Ohio	Henderson	372	2,250	Ste. Genevieve Limestone (Mississippian)	
	88808	Liberty National 1 Smith	Henderson	364	2,600	Salem Limestone (Mississippian)	
	25128	Styles 1 Gab Hart	Daviess	387	3,738	lower part of Devonian	
52700	163589	Continental Res. 1 Weatherholt	Spencer, Ind.	438	5,697	upper Knox Group (Ordovician)	
46003	155163	Quatro Energy 1 Jeffery	Spencer, Ind.	409	5,045	upper Knox Group (Ordovician)	
28660	27909	Reynolds and Vincent 1 Marxson	Hancock	519	3,281	undifferentiated Ordovician	
23171	27913	LH Drilling 1 Chapman	Hancock	381	3,002	undifferentiated Ordovician	X
22452	27906	Zogg Oil 1 Yunker-Hart	Hancock	614	2,653	upper part of Ordovician	X
25646	2484	Langford Oil 1 Knight Bros.	Breckinridge	402	6,040	Copper Ridge Dolomite (Cambrian)	X
26264	26546	Texas Gas 1 Kroush	Breckinridge	680	1,644	undifferentiated Silurian	X
98673	130055	Daugherty DPI-2010-18 Walls	Meade	657	1,138	Copper Ridge Dolomite (Cambrian)	
3873	13805	Duchscherer 1 Pack	Meade	633	3,380	Copper Ridge Dolomite (Cambrian)	X

No. 1 Marvin Blan well in Hancock County. Although the Copper Ridge is dominated by dense dolomite, a number of discrete porosity zones may be conducive to injection. According to Rick Bowersox at the Kentucky Geological Survey, brines were successfully injected into a naturally fractured interval of the basal Copper Ridge from 7,180 to 7,455 ft in the Marvin Blan well. Two subsequent tests of the upper Copper Ridge in the test well failed shortly after pumping began because of communication around the packers through the formation's porosity system. Better injection tests were obtained through the use of a single packer and injecting into the full wellbore below. Injection rates of as much as 14 barrels/min were achieved, with wellhead pressures of 285 to 550 psi.

CO_2 injection began on August 19, 2009. A total of 323 short tons of CO_2 was injected openhole into the upper and lower Knox at the pumping equipment maximum rate of 4.1 barrels/min. This was the first demonstration of CO_2 injection in the Knox in the United States. Temperature logs were run after injection to verify CO_2 placement. The wellbore was then flushed with brine and temporarily abandoned with downhole pressure monitoring in place, pending additional testing to be completed in early 2010. Final results and a report will be posted at the Kentucky Consortium for Carbon Storage Web site.

Further testing in the Blan well will be funded as part of a U.S. Department of Energy grant from the American Recovery and Reinvestment Act to the University of Illinois, Illinois State Geological Survey, and its partners, including the Kentucky Geological Survey. More information on the Copper Ridge in the Blan well can be found at the Kentucky Consortium

Ohio River West-Central

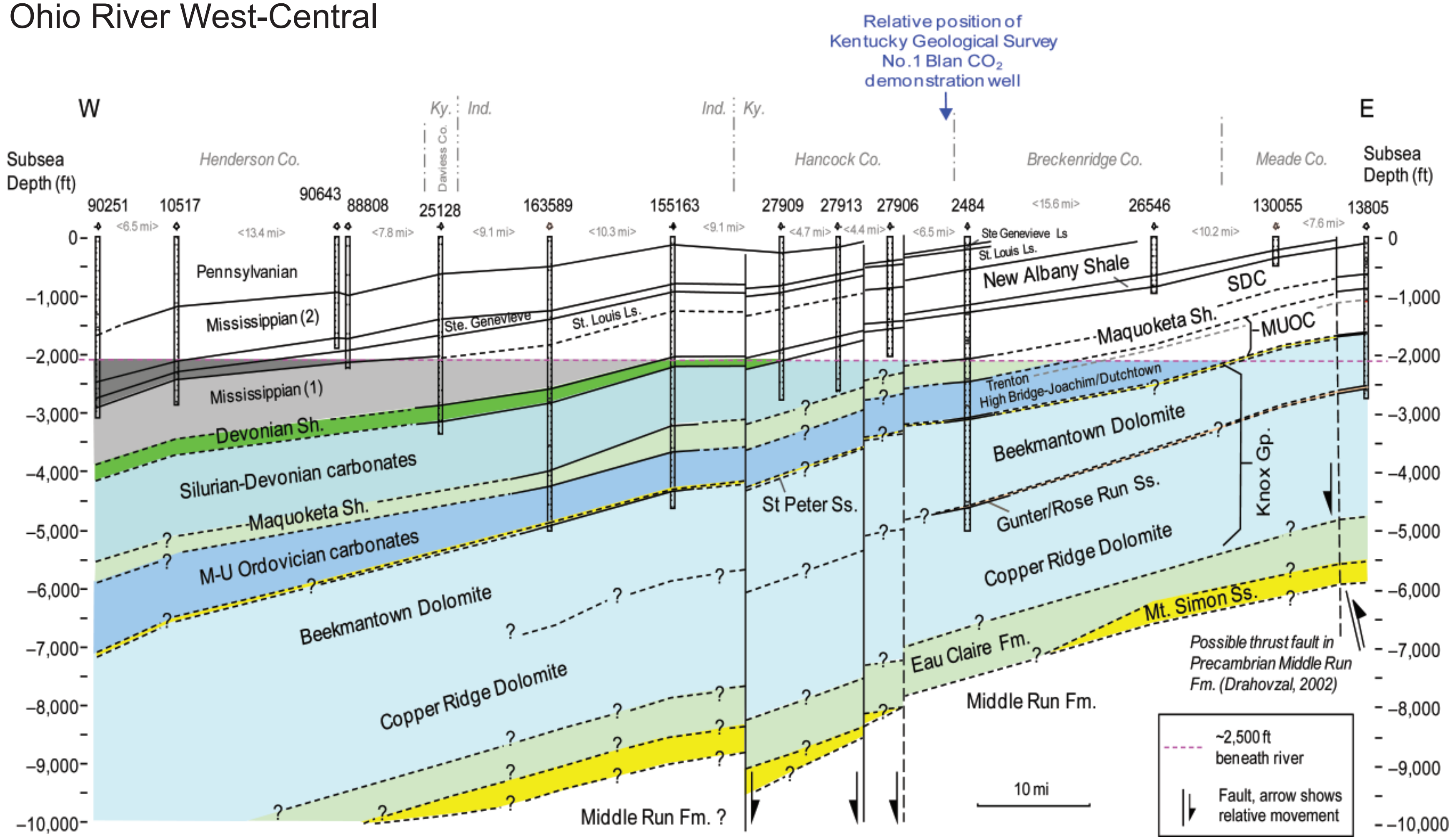

Figure 4.68. Ohio River (west-central) cross section showing intervals discussed in the "Rock Unit Summary." Intervals are color-coded according to their generalized carbon-storage category, as shown in Figure 4.5. Location of the section is shown in Figure 4.67. Wells used in this section are shown in Table 4.13. Expanded cross section with geophysical logs is shown in Plate 4.2. Faults that can be mapped at the surface are shown as solid at the top and dashed downward on the cross section. Faults that are not visible on the surface, but have been detected at depth from seismic analysis, are shown as solid at the bottom and dashed upward in the cross section. Basement depths are based on preliminary seismic analyses and subject to change. Surface faults connect to basement faults, but the level at which they connect or split is uncertain without specific data for that location. Miss (1)=lower part of the Mississippian from the Salem Limestone to the New Providence Formation, Miss (2)=upper part of the Mississippian strata from the base of the Pennsylvanian to the top of the Ste. Genevieve Limestone, MUOC=Middle–Upper Ordovician carbonate interval, SDC=Silurian–Devonian carbonate interval.

for Carbon Storage Web site (www.uky.edu/KGS/Kentucky Consortium for Carbon Storage/).

Gunter–Rose Run Sandstone. The Gunter Sandstone is penetrated in two of the wells along this section (Fig. 4.69, Plate 4.2). The Gunter Sandstone of the Illinois Basin is equivalent to the Rose Run Sandstone in the Appalachian Basin. Data have been collected on the regional distribution and carbon storage capacity of the Rose Run in eastern Kentucky, but there has been little work on the equivalent Gunter Sandstone in western Kentucky or the Illinois Basin. The Gunter was penetrated from 5,090 to 5,230 ft in the Kentucky Geological Survey No. 1 Marvin Blan well in Hancock County. Core from the upper part of the Gunter in the Blan well shows it is composed of fine-grained, well-rounded quartz sand in a dolomite matrix interbedded with thin dolomites. This sandstone had good porosity and was part of the openhole injection zone tested in the Blan well (Bowersox and Williams, 2009). More work is needed to determine trends in thickness and porosity in the Gunter Sandstone deeper into the Illinois Basin. More information on the Gunter in the Blan well can be found at the Kentucky Consortium for Carbon Storage Web site.

Upper Knox–Beekmantown Dolomite. Four wells reach the top of the Beekmantown along this section, but only two completely penetrate the unit (Fig. 4.68, Plate 4.2). The Beekmantown is approximately 2,200 ft deep on the eastern end of the section and deepens to 7,500 ft on the western end of the section. It is penetrated in the Langford Oil No. 1 Wright Brothers well at 3,474 ft and in the Duchscherer No. 1 Pack well, Meade County, at 2,282 ft. In these wells the dolomite thickens westward as it deepens. The Beekmantown may also thicken into the northeast–southwest-oriented graben in Hancock County (Fig. 4.68).

In the Duchscherer No. 1 Pack well, sulfurous saline water was encountered at 2,860 ft (578 ft from the top of the Knox) and from 2,880 to 3,380 ft (598 to 1,098 ft from the top). There was also a good gas show at 3,008 ft (726 ft from the top). No gas or water were encountered in the Beekmantown in the Kentucky Geological Survey No. 1 Blan test well, but several discrete porosity intervals were noted on geophysical logs. The Beekmantown was part of the openhole injection zone tested in the Blan well. More information on the upper Knox in the Blan well can be found at the Kentucky Consortium for Carbon Storage Web site.

St. Peter Sandstone. The St. Peter interval is penetrated in four wells along this section (Fig. 4.68, Plate 4.2), although sandstone is not identified on most of the drillers' logs for these wells. The St. Peter is at a depth of approximately 7,000 ft on the western end of the section and shallows to 2,000 ft on the eastern end of the section. In the Langford Oil and Gas No. 1 Knight Brothers well, Breckinridge County, the St. Peter is at

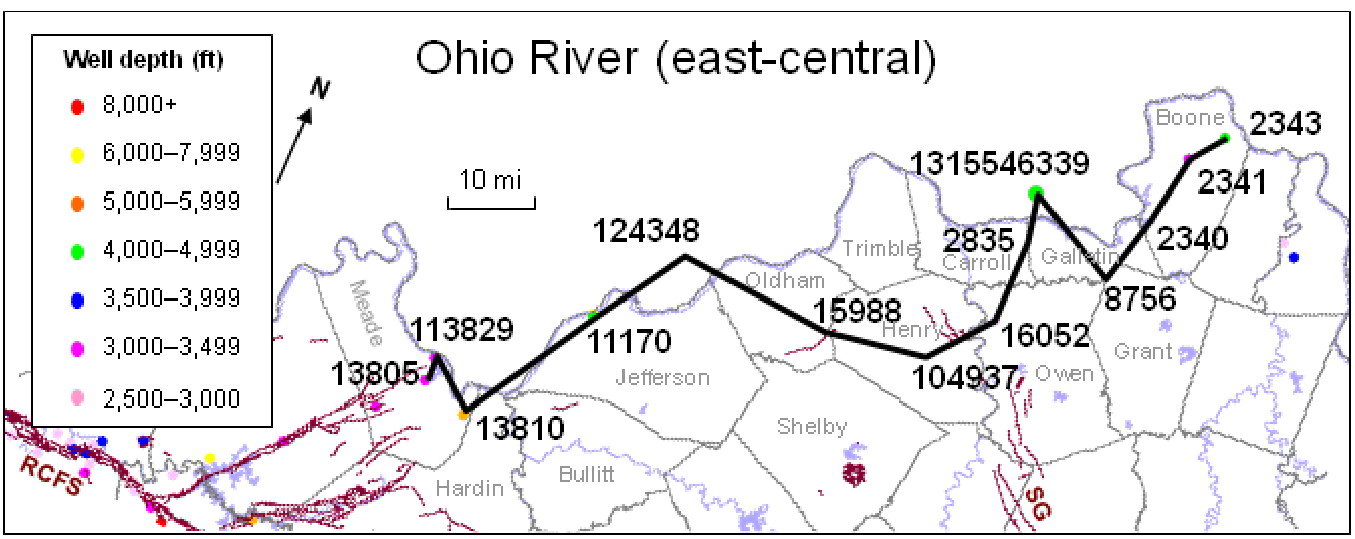

Figure 4.69. Location of the Ohio River (east-central) cross section. Wells used in the section are labeled by their record number (see Table 4.15). Locations of other wells in the vicinity are color-coded for depth. Wells less than 2,500 ft in depth are not shown. Map is oriented to better fit on the page. Faults exposed at the surface are shown as brown lines. The amount of offset at depth on some of these faults is uncertain. MS = Muldraugh structure. RCF = Rough Creek Fault System. SG = Sweitzer Graben.

3,422 to 3,472 ft (50 ft of sandstone and carbonate). In the Duchscherer No. 1 well, Meade County, the sandstone is reported from 2,258 to 2,280 ft (22 ft thick). Although several of the wells intersect the St. Peter at depths of less than 7,000 ft, where it has the possibility of porosity (Hoholick and others, 1984), wells that penetrated the St. Peter along this cross section encountered well-cemented (tight, low-porosity) sandstone. The sandstone could be stimulated to increase porosity as a secondary injection target, but it does not appear to be well suited as a primary target for large-scale injection along this stretch of the river. In the recently drilled Kentucky Geological Survey No. 1 Blan well, only 6 in. of sandstone was recorded in the St. Peter interval, which otherwise consisted of nonporous dolomite (Bowersox and Williams, 2009). That said, it should be investigated in any test of the underlying Knox in case of local thickness and secondary porosity development or a chance for stacked, thinner reservoirs.

Middle-Upper Ordovician Carbonates. This interval is penetrated in four wells along this section (Fig. 4.68, Plate 4.2). No porosity or saline water were noted in the Middle-Upper Ordovician carbonates along this section. Very little oil and gas has been produced, and evidence of significant porosity in this interval in western Kentucky is lacking. Also, there is little evidence for significant porosity in this interval in the southern part of the Illinois Basin (see, for example, Seyler and Cluff, 1991). In the Kentucky Geological Survey No. 1 Blan well, the Black River part of the interval (521 ft) was considered a secondary confining interval (Bowersox and Williams, 2009).

Upper Ordovician Shale. The Maquoketa Formation is penetrated in four wells along this section and shallows from 6,000 to 1,000 ft deep (Fig. 4.68, Plate 4.2). The unit thickens as the underlying Trenton Limestone thins in a depositional feature called the Sebree Trough (Kolata and others, 2001). The Maquoketa may be more than 470 ft thick in the Duchscherer No. 1 Pack well on the eastern end of the section. It was 395 ft thick at a depth of 2,787 ft in the recently completed Kentucky Geological Survey No. 1 Blan well in Hancock County (Bowersox and Williams, 2009). Most of the interval is dominated by shale and is considered a regional confining interval. Where the Maquoketa is unfaulted, it would likely provide an adequate seal to underlying injection. West of Breckinridge County, the Maquoketa is more than 2,500 ft deep and could be used as a confining interval that would keep any CO_2 injected into underlying units in a supercritical state.

Silurian-Devonian Carbonates and Sandstones. Nine wells reach this interval along this section, and four of the wells penetrate the entire interval (Fig. 4.70, Plate 4.2). Evidence of significant porosity or saline water in this interval along this section is sparse, and little oil and gas has been produced from Silurian-Devonian carbonates in western Kentucky. Silurian and Devonian oil and gas has been produced from the Jeffersonville and Louisville Limestones in the Doe Run Field on the Ohio River in eastern Meade County near the eastern end of the section. Production is from 700 to 800 ft deep, too shallow for carbon storage. Also, research (see, for example, Seyler and Cluff, 1991) has extended the Silurian reef trend south from Illinois and Indiana into northern Hancock County, along the river. Silurian reefs are significant reservoirs to the north in Indiana and Michigan, but the trend seems to stop in Kentucky; if more reefs were found in Kentucky along the trend, they would be shallower than 2,500 ft, and hence unlikely reservoirs for miscible carbon storage.

Devonian Shale. The New Albany Shale is penetrated in all but the four westernmost (deepest) wells in this section (Fig. 4.68, Plate 4.2). It thickens and deepens from east to west along the section. The shale is 90 ft thick, at a depth of 621 ft, on the eastern end of the section, and thickens and deepens on the western end of the section near Henderson to more than 3,800 ft (Schwalb and Potter, 1978).

Gas is produced from the shale in Breckinridge and Meade Counties, so there may be possibilities for enhanced gas recovery with CO_2 along the eastern part of this section. The Devonian shale is a potential unconventional carbon sequestration reservoir for enhanced methane recovery (see Nuttall and others, 2005). Planned demonstration tests in eastern Kentucky will help to better delineate the parameters under which injection into the shale for enhanced recovery may be possible.

The New Albany is known as a regional confining interval. Only along the parts of the river where the New Albany is more than approximately 2,500 ft deep could it be used as a confining interval that would keep any CO_2 injected into underlying units in a supercritical state.

Shallower Porosity Horizons Deeper than 2,500 ft. Several Mississippian formations that are conventional

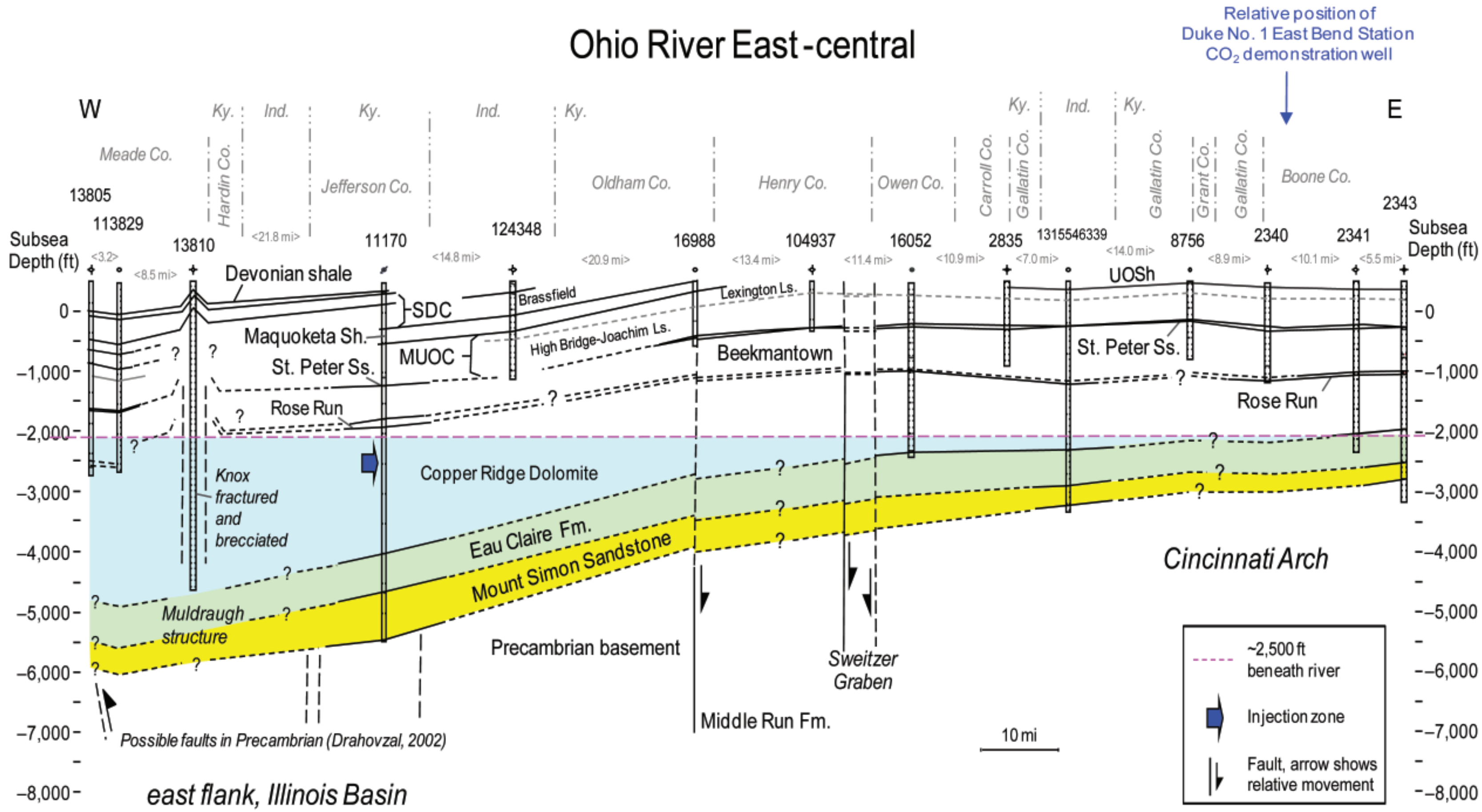

Figure 4.70. Ohio River (east-central) cross section showing intervals discussed in the “Rock Unit Summary.” Intervals are color- coded according to their generalized carbon-storage category, as shown in Figure 4.5. Location of the section is shown in Figure 4.69. Wells used in this section are listed in Table 4.15. Expanded cross section with geophysical logs is shown in Plate 4.3. Faults that can be mapped at the surface are shown as solid at the top and dashed downward on the cross section. Faults that are not visible on the surface, but have been detected at depth from seismic analysis, are shown as solid at the bottom and dashed upward in the cross section. Surface faults connect to basement faults, but the level at which they connect or split is uncertain without specific data at that location. MUOC=Middle–Upper Ordovician carbonate interval, SDC=Silurian–Devonian carbonate interval.

oil and gas targets in this part of the basin are at depths of more than 2,500 ft in Henderson County, on the western end of the cross section (Fig. 4.68, Plate 4.2). These horizons are not discussed in the "Rock Unit Summary" because they were shallower than the Devonian shale, but they may offer small-scale injection possibilities or enhanced oil and gas opportunities. Summaries for known Mississippian porosity (oil and gas production) include field studies and overviews in Miller (1968), Zupann and Keith (1988), and Leighton and others (1991), as well as many Kentucky Geological Survey pool and field studies.

The Mississippian Salem and Warsaw Limestones are at depths of more than 2,500 ft west of the Styles No. 1 Gab Hart well in Daviess County. The Mississippian Ste. Genevieve Limestone and McCloskey reservoirs are more than 2,500 ft deep in the westernmost part of the section (Fig. 4.68, Plate 4.2). The Ste. Genevieve Limestone is heavily penetrated by oil and gas wells in the westernmost part of the section, and the large number of wells might provide pathways for leakage for a large-scale injection into this unit.

Coals Deeper than 1,000 ft. In the westernmost well (Fig. 4.68, Plate 4.2), the top of the lowest Caseyville Sandstone (Lower Pennsylvanian) is more than 1,100 ft below sea level. Sometimes a thin coal is above this sandstone, but its occurrence cannot be confirmed on available geophysical logs. Also, coals in this stratigraphic position are generally thin (less than 24 in.) and not laterally extensive, so would not likely be conducive to coalbed methane recovery with CO_2 or carbon storage.

Ohio River (West-Central) Summary. The Mount Simon is likely too deep for carbon storage on the western part of the Ohio River (west-central) section, and was absent in the Kentucky Geological Survey No. 1 Marvin Blan well, Hancock County, drilled by the Kentucky Consortium for Carbon Storage in the summer of 2009. The St. Peter Sandstone has little porosity where it has been encountered. There appear to be carbon storage possibilities in the Knox Group (including the Gunter Sandstone), which was tested in the Marvin Blan well. Use of the Knox for large-scale storage would require stacking of multiple porosity zones within the Knox, or openhole completion, as was done in the Marvin Blan test well, because most known porosity intervals in Knox wells along this section are relatively narrow. Stimulation might also be required for the Knox for large-scale sequestration.

Mississippian strata may offer possibilities for local (at least small-scale) carbon storage where they occur at more than 2,500 ft depth in Henderson County. Mississippian reservoirs are targets for oil and gas exploration, however, and will have many existing well penetrations that would have to be considered as potential pathways for leakage in any injection project. In the western part of this section, two oil fields have had production in excess of 5 million barrels: the Birk City Consolidated (Henderson and Daviess Counties) and Griffith Consolidated (Daviess County) (Brownfield and others, 1968). Production from these fields is mostly from Mississippian strata, and is shallower than 2,500 ft. Both are discussed in chapter 2 of this report. In the future, when CO_2 is available for much less than its current price, it might be used to repressurize old oil fields or for enhanced oil and gas recovery, but these fields would not be suitable for large-volume storage in tandem with enhanced oil and gas recovery because of their shallow depths.

Ohio River (East-Central)

The Ohio River (east-central) section extends from the Meade-Hardin County line to Boone County and the greater Cincinnati metropolitan area (Fig. 4.63). Large towns along this stretch of the river include Louisville and the western part of the Cincinnati metro region. Fossil-fuel-powered electricity-generating facilities along this stretch of the river are listed in Table 4.14. Three additional fossil-fuel-fired power stations are located on the Indiana side of the river.

The Ohio River (east-central) section was constructed with data from 14 wells, two of which are in Indiana (Fig. 4.70, Table 4.15, Plate 4.3). Two of the wells reach basement and most reach at least the top of the Knox Group. Drillers' descriptions of cuttings are available for the Louisville Gas No. 16 U.S. Government well, the DuPont No. 1 WAD Fee well, and the Ford No. 1 Conner well. Core reports are available online for the Knox in the Union Light No. 2 Thomason and the Cincinnati Gas No. 1 Bender wells. The DuPont well was an acid and water waste-injection well into the Copper Ridge Dolomite and provides useful data for potential future CO_2 injection into the Knox. Core from the DuPont well is stored in the Kentucky Geological Survey Well Sample and Core Library in Lexington.

Structure and Faulting. This cross section crosses the crest of the Cincinnati Arch, so strata are relatively flat-lying compared to strata in sections to the east and west

Table 4.14. Electric-power-generating stations along the Kentucky side of the east-central part of the Ohio River. Data from Kentucky Public Service Commission (June 10, 2008) and Energy Information Administration (2006).

Owner	*Plant Name*	*Capacity (MW)*	*Fuel*	*County*
Louisville Gas & Electric (E.ON)	Mill Creek	1,717	coal	Jefferson
Louisville Gas & Electric (E.ON)	Cane Run	645	coal	Jefferson
Louisville Gas & Electric (E.ON)	Cane Run	16	natural gas	Jefferson
Louisville Gas & Electric (E.ON)	Paddy's Run	227	natural gas	Jefferson
Louisville Gas & Electric (E.ON)	Waterside	45	natural gas	Jefferson
Louisville Gas & Electric (E.ON)	Zorn	18	natural gas	Jefferson
Dynegy	Bluegrass	618	natural gas	Oldham
Louisville Gas & Electric (E.ON)	Trimble County	1,194	natural gas	Trimble
Louisville Gas & Electric (E.ON)	Trimble County	566	natural gas	Trimble
Kentucky Utilities (E.ON)	Ghent	2,226	coal	Carroll
Duke Energy	East Bend No. 2	669	coal	Boone
Duke Energy	Miami Ft. Unit 6	168	coal	Hamilton (Ohio)

(Fig. 4.69, Plate 4.3). On the western end of the section (Rock Haven and Fort Knox 7.5-minute quadrangles) is a local structural anomaly, informally called the "Muldraugh structure" (MS in Figure 4.69) (Withington and Sable, 1969). The domal structure is approximately 2 mi wide and there is 360 ft of structural relief on the top of the New Albany Shale. The Louisville Gas & Electric No. 16 well reported Knox directly beneath Devonian black shale, but the well appears to have much of the normal Devonian-Silurian section. Freeman (1951) reported that the inferred Knox was brecciated beneath the Silurian in wells on the structure. Freeman (1951) and log descriptions from the Louisville Gas and Electric No. 16 well described the structure as a buried cryptoexplosive structure. Cryptovolcanic and cryptoexplosive structures were names applied to circular, domal structures of unknown origin. Many were subsequently inferred to represent either meteor impact sites or buried volcanic deposits. Cressman (1981) argued against an impact origin for the Muldraugh structure. Regardless of its origin, correlating rocks in the deeper part of the well east and west of the structure is difficult, and fracturing is likely in the vicinity of the structure. Westward, in Henry County, a series of northwest–southeast-oriented faults occur along the Sweitzer Graben trend (SG in Figure 4.69). Elsewhere along the section, there are no significant structures across the river.

Precambrian Basement. The Precambrian is penetrated in three wells along this section (Fig. 4.69, Plate 4.3). The depth to the top of the Precambrian gradually shallows from west to east. The top of the Precambrian is approximately 7,000 ft below sea level (approximately 7,500 ft deep) at the Breckinridge-Meade County line, and shallows to less than 3,000 ft below sea level (less than 3,500 ft deep) in Boone County. This, however, is not the depth to basement. A thick sequence of Precambrian sedimentary rocks and volcanics called the Middle Run Formation (Drahovzal and others, 1992) is preserved in the East Continent Rift Basin, a Precambrian trough beneath the Cincinnati Arch. Along this part of the river, the western margin of the rift basin is near the Jefferson-Oldham County line. West of that margin, Precambrian crystalline basement is at a depth of approximately 5,000 ft below sea level (approximately 5,500 ft deep) and consists of igneous rocks of the Granite-Rhyolite Province. Eastward, the depth to crystalline basement increases dramatically into the rift basin to depths of 15,000 to 22,000 ft below sea level. A series of faults in the basement, which do not penetrate overlying Paleozoic strata, result in fault blocks beneath the river with several thousand feet of offset (Drahovzal and others, 1992; Drahovzal, 2002). None of the wells along this part of the river reach total depth in crystalline basement rocks.

Middle Run Formation. The Middle Run is a Precambrian unit of mixed sedimentary and volcanic rocks (see "Rock Unit Description"). Most of what is known about this unit in Kentucky is based on seismic data and is summarized in Drahovzal and others

Table 4.15. Information on wells used for the Ohio River (east-central) cross section. Record numbers can be used to view well data in the KGS Oil and Gas Database. The recently drilled Duke No. 1 East Bend Station well, a carbon storage test well, is in a position near the Cincinnati Gas No. 1 Bender well in this section.

Permit	*Record*	*Well Name*	*County*	*Elevation (ft)*	*Total Depth (ft)*	*Formation at TD*	*Samples*
3873	13805	Duchscherer 1 Pack	Meade	633	3,380	Copper Ridge Dol (Cambrian)	X
87775	113829	Mercury Olin 1 Olin Corp.	Meade	456	3,150	upper Knox Group (Ordovician)	
18738	13810	Louisville Gas 16 U.S. Gov.	Meade	710	5,350	Copper Ridge Dolomite (Cambrian)	X
24756	11169	E I DuPont de Nem 1 WAD E I DuPont	Jefferson	452	6,011	Middle Run Formation (Precambrian)	core
23684	124348	Indiana Gas 1 Oglesby	Clark, Ind.	518	1,650	upper Knox Group (Ordovician)	?
11891	15988	Louisville Gas 1 Blakemore	Oldham	836	1,423	upper Knox Group (Ordovician)	core
82763	104937	IHTGIW Inc. 1 Holmes	Henry	862	1,200	upper Knox Group (Ordovician)	X
18849	16052	Tennessee Corp. BT3 O'Donovan	Owen	467	2,900	Eau Claire Formation (Cambrian)	core
29557	2835	Minex 1 Robinson	Carroll	679	1,605	upper Knox Group (Ordovician)	
46339	159292	Ashland Explora-tion 1 Sullivan	Switzer-land, Ind.	779	4,151	Middle Run Formation (Precambrian)	?
11105	8756	Union Light 2 Thomason	Gallatin	553	1,347	upper Knox Group (Ordovician)	
	2340	Cincinnati Gas 1 Bender	Boone	461	1,656	upper Knox Group (Ordovician)	core
	2341	Continental 1 Snow	Boone	860	3,215	Eau Claire Formation (Cambrian)	X
	2343	Ford 1 Conner	Boone	908	4,089	Middle Run Formation (Precambrian)	X

(1992). Along this part of the Ohio River, the Middle Run was penetrated in the Ashland No. 1 Eichler well in Switzerland County, Ind., the Ford No. 1 Conner well in Boone County, Ky., and the DuPont No. 1 WAD Fee well in Jefferson County, Ky. (Fig. 4.69, Plate 4.3). Only a small part of the entire thickness of the Middle Run was penetrated in these wells, but the rocks that were penetrated showed little porosity. The unit varies from approximately 2,500 ft thick in northern Boone County to 20,000 ft thick in Trimble and Carroll Counties. Drahovzal (2002) interpreted a strike-slip fault in the Middle Run near the trend of the Sweitzer Graben. West of this fault (including in the DuPont well in Jefferson County), basalts occur in the Middle Run. The basalts may extend (based on gravity and magnetic anomalies) to the western end of this section (Drahovzal, 1997). The lack of porosity in the few wells that have penetrated the unit is discouraging, but the Middle Run is the only possibility for injection other than the overlying Mount Simon Sandstone along this part of the river because most of the Knox is less than 2,500 ft deep. If future wells are drilled to test the Mount Simon in this region, they should also test at least the upper part of the Middle Run to see if there might be additional porosity that could be used.

Mount Simon Sandstone. The Mount Simon Sandstone is penetrated in three wells along this section and is likely continuous across this stretch of the river (Fig. 4.69, Plate 4.3). The sandstone shallows from west to east up the Cincinnati Arch, from approximately 6,000 ft deep on the western end of the section to 3,430 ft deep in the Ford Conner well, on the eastern end of the cross section. The sandstone was drilled at the DuPont site in Louisville in 1971 and 1972 as a potential injection reservoir for an acidic pickling brine. In the No. 1 Waste Acid Disposal well at this location, the Mount Simon is 752 ft thick, and the top of the unit is at a depth of 5,192 ft. Extensive testing and stimulation showed that the sandstone had less porosity and permeability than needed for DuPont's injection needs. The sandstone is estimated to be 500 ft thick on the western end of the section, thickens to 791 ft in the DuPont No. 1 WAD well in Louisville, and thins east to 270 ft in the Ford No. 1 Conner well, Boone County.

In the summer of 2009, the Battelle No. 1 Duke Energy East Bend Station well was drilled in Boone County as part of the Midwest Regional Carbon Sequestration Partnership's regional carbon storage testing. The primary goal of the well was characterization and testing of the Mount Simon Sandstone. In the well, the Mount Simon is 300 ft thick, at depths of 3,232 to 3,532 ft. Preliminary results indicate 1,000 tons of CO_2 were successfully injected into the lower part of the Mount Simon. Pump rates of four barrels/min were achieved, which was the limit of the pumps. This was the first injection of CO_2 into the Mount Simon Sandstone in the nation. Its relative position is shown in Figure 4.69. More information, including fact sheets for this project, can be found at the Midwest Regional Carbon Sequestration Partnership Web site (216.109.210.162/).

Eau Claire Formation. Five wells reach the upper Eau Claire and three wells penetrate the entire unit along this section (Fig. 4.69, Plate 4.3). The Eau Claire is 568 ft thick at a depth of 4,520 ft in the DuPont No. 1 WAD fee well and 556 ft thick at 2,872 ft in the Ford No. 1 Conner well on the east end of the section. The Eau Claire is dominated by shale and is more than 2,500 ft deep along the section, so it should provide an adequate seal to underlying injection in the Mount Simon if attempted.

Lower Knox–Copper Ridge Dolomite. The Copper Ridge is penetrated in five of the wells in this section (Fig. 4.69, Plate 4.3). The top of the Copper Ridge is less than 2,500 ft deep in eastern Meade County to the east, although the lower half of the Copper Ridge is more than 2,500 ft deep from Oldham County west. Analysis of some of the shallow wells may provide useful data for this unit at greater depths off of the Cincinnati Arch where there are fewer penetrations.

In the DuPont No. 1 WAD well, acidic waste waters were injected into the Copper Ridge at a depth of approximately 3,000 ft. Injection was subsequently terminated because of changes in the plant. Subsequent monitoring of the injection zone recorded the development of two elongate caverns, each several hundred feet in length and 40 to 60 ft in height and width (Clark and others, 2005). The acidic injectate appears to have enlarged existing voids oriented along fractures. In fractured reservoirs, the orientations of the fractures need to be considered when modeling areas of influence and planning monitoring stations. Dual-porosity models may be needed for more accurate predictions of plume orientation and area. An interesting side effect of the acidic injectate was the formation of CO_2 from chemical interaction with the carbonates in the Knox. The CO_2 was safely contained within the caverns, so were sealed by the surrounding carbonates of the upper Knox. In 1990, the Environmental Protection Agency issued DuPont an approved "chemical fate" no-migration demonstration for the site, which means EPA considered the injected wastes safely contained within the Knox reservoir. These wells have useful data for future carbon-sequestration projects in the region.

Farther updip, porosity was also found in the Copper Ridge in the Continental No. 1 Snow well. A hole full of sulfurous, saline water was reported in this well after it penetrated a porosity zone at a depth of 2,109 ft. This depth would be too shallow for carbon sequestration, but similar zones might occur at appropriate depths between the DuPont and Continental wells.

Rose Run–Gunter Sandstone. The Rose Run–Gunter is penetrated in six of the wells along this section, but is too shallow for miscible CO_2 storage (Fig. 4.69, Plate 4.3). Regional mapping suggests the Rose Run Sandstone thins eastward from the Appalachian Basin. Several wells show porosity on the eastern end of the section where the overlying Beekmantown Dolomite (upper Knox) thins beneath the unconformity at the top of the Knox. More work is needed to determine trends in thickness and porosity in the Rose Run and Gunter Sandstones deeper into the Illinois Basin.

Upper Knox–Beekmantown Dolomite. The Beekmantown is penetrated in all of the wells along this section, but is too shallow for miscible CO_2 storage (Fig. 4.69, Plate 4.3). It has, however, been used successfully for natural-gas storage in the area, and well-log data may be useful for interpretation of this unit downdip, where miscible injection would be possible. The Louisville Gas No. 1 Blakemore well is in the Ballardsville Gas Storage Field, an abandoned field developed in a stray sand in the upper Knox (and possibly the overlying St. Peter Sandstone). The porosity zone was developed in the Beekmantown, beneath the unconformity at the top of the Knox, on the downthrown side of the Ballardsville Fault. The recently drilled Battelle No. 1 Duke Energy East Bend Station well also encountered porosity in a sandstone in the upper Knox.

The Union Light No. 2 Thomason well is in the Eagle Creek Gas Storage Field. This field is developed on a small conical high on the Knox unconformity surface. The buried Knox hill has 40 to 60 ft of structural closure (Greb and others, in press). In the Eagle Creek Field, the variability and distribution of silica influences horizontal and vertical porosity and permeability. The average porosity of the reservoir is 8 percent. The average horizontal permeability is 202 md, with a range from less than 1 to 5,270 md. High-permeability zones may be related to fractures, which were noted in one well. Although capacity data are not available for this field, gas storage fields along the unconformity in neighboring Indiana have gas (methane) storage capacities of 0.49 to 1.39 mcf (Keller and Abdulkareem, 1980; Keller, 1998). Current use of the Knox at depths of less than 2,500 ft for methane storage should provide some public reassurance about the use of the Knox at greater depths for carbon storage.

Porosity has been noted in several other wells along this line of section in the Beekmantown. In the Louisville No. 1 Blakemore well, saline water was encountered at 1,397 ft, 103 ft below the top of the Knox. The Minex No. 1 Robinson well had (fresh?) water with sulfur taste and odor 37 ft below the top of the Knox, and the Tennessee Corp. No. BT3 O'Donovan had a porosity zone 40 to 50 ft below the top of the Knox. A show of saline water was also encountered near the base of the Beekmantown in the Continental No. 1 Snow well at 1,745 ft.

St. Peter Sandstone. The St. Peter is too shallow for CO_2 storage along this section of the river (Fig. 4.69, Plate 4.3). Data from these shallow wells might be helpful for analysis of the sandstone where it is deeper and there are fewer penetrations. Analysis of these shallow wells may also aid in determining the stratigraphic position of a sandstone reported as an upper "Knox sand" (is it in the Knox or is it really the St. Peter?). Water was encountered in the Minex No. 1 Robison well at 1,077 ft, in the Ford No. 1 Conner well at 1,225 ft, and in the Continental No. 1 Snow well at 1,225 ft, which suggests some porosity in the sandstone.

Units Shallower than the St. Peter Sandstone. These units are not discussed for this section because they are too shallow to be considered for carbon storage along this part of the river. Upper Ordovician strata occur at the surface east of Oldham County. Silurian and Devonian strata occur at the surface in Jefferson and Oldham Counties. The Maquoketa Shale, which is a primary confining interval to the west, is too shallow to be considered a confining interval along this part of the river.

Ohio River (East-Central) Summary. For the most part, the Mount Simon is the only unit deeper than 2,500 ft that has a possibility for large-volume carbon storage along the Ohio River (east-central) section. The sandstone was successfully tested with a small amount of CO_2 in the Battelle No. 1 Duke Energy East Bend Station well, Boone County, as part of the Midwest Regional Carbon Sequestration Partnership's phase II demonstration projects. The Copper Ridge Dolomite west of Louisville, Jefferson County, also has potential. The Copper Ridge (lower Knox) is at miscible depths and was successfully used for liquid waste injection at the DuPont plant. Carbon dioxide was formed as a result of acidic reaction with the carbonate reservoir and was safely held within the Copper Ridge at the DuPont site. The porosity zones at the DuPont plant were elongate voids, which would be relatively small reservoirs relative to industrial-scale sequestration. Whether or not similar zones could be found for large-scale injection or multiple porosity intervals could be combined in openhole injections to increase the net capacity of the interval is uncertain, but the DuPont wells provide significant data for potential injection projects to the west (downdip and deeper).

Ohio River (East)

The Ohio River (east) cross section extends from western Boone County to Boyd County (Figs. 4.63, 4.71). Large towns along this stretch of the river include the eastern part of the Cincinnati metro region, Maysville, and Ashland. Fossil-fuel-powered electricity-generating facilities along this stretch of the river are listed in Table 4.16. Five additional fossil-fuel-powered electricity-generating stations are located along the Ohio side of the river.

The Ohio River (east) section is constructed from 10 wells, three from Ohio (Figs. 4.71–4.72, Table 4.17). All the wells except the easternmost penetrate the Knox Formation, and nine reach total depths in Precambrian basement. Although this part of the state has relatively few deep (greater than 2,500 ft) wells, the cross section includes most of the basement tests, which provide reasonable confidence in the correlation of subsurface strata. Drillers' descriptions of cuttings are available for three of the wells: the Ford No. 1 Conner, United Fuel Gas Co. No. 9061T Rawlings, and the Thomas Ralph N. No. 1 Adams. Ryder and others' (1997) cross section of the central Appalachian Basin parallels the Ohio River (east) section for part of its length (and used some of the same wells), and provides a good reference for the subsurface geology of the area.

Structure and Faulting. The Ohio River (east) section straddles the Cincinnati Arch in the west, with the apex of the arch near the Ashland Oil and Refining No. 1 Wilson well in Campbell County. It extends east into the Appalachian Basin. In general, strata west of the apex of the arch have a shallow westward dip and strata east of the apex have a slight eastward dip (Fig. 4.72, Plate 4.4). The eastward dip into the basin causes more potential reservoirs to occur at depths of more than 2,500 ft eastward along the river than along the apex of the arch. Only a couple of faults occur along the line of section, and all are basement faults with no surface expression. These faults were interpreted from seismic and geophysical data. The Grenville Front is marked by a fault at depth in western Mason County. This fault separates two different types of Precambrian basement

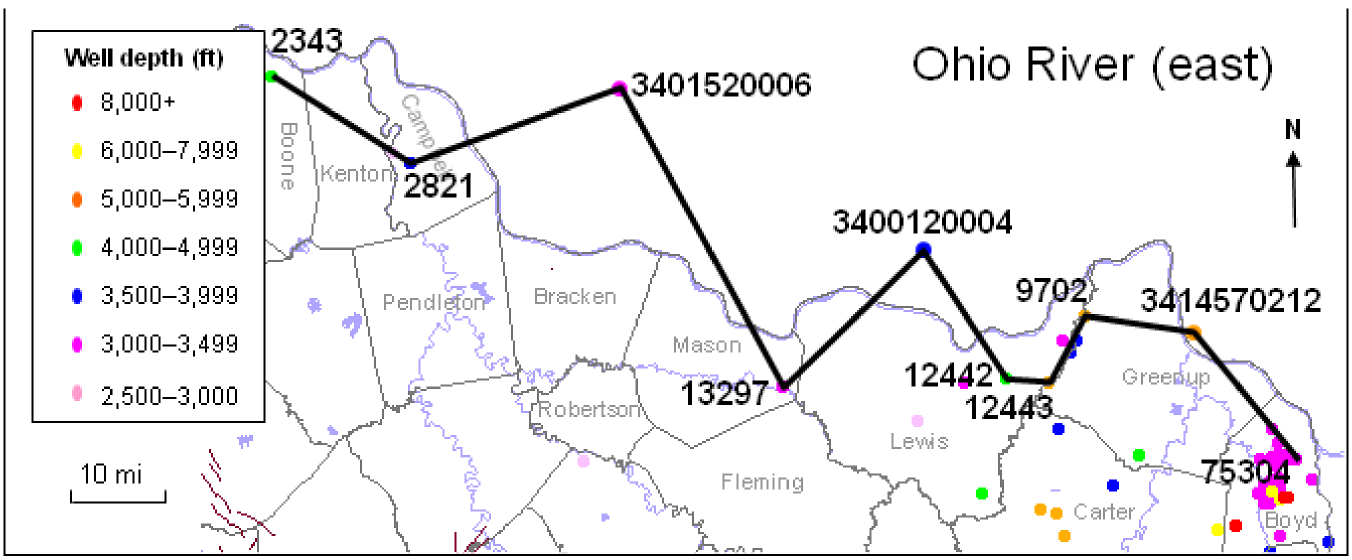

Figure 4.71. Location of the Ohio River (east) cross section. Wells used in the section are labeled by their record number (see Table 4.17). Locations of other wells in the vicinity are color-coded for depth. Wells less than 2,500 ft in depth are not shown. Faults exposed at the surface are shown as brown lines.

Table 4.16. Electric-power-generating stations along the Kentucky side of the eastern part of the Ohio River. Data from Kentucky Public Service Commission (June 10, 2008) and Energy Information Administration (2006).

Owner	*Plant Name*	*Capacity (MW)*	*Fuel*	*County*
Duke Energy Generation Service	Silver Grove	20	natural gas	Campbell
East Kentucky Power Coop.	H.L. Spurlock	1,279	coal	Mason

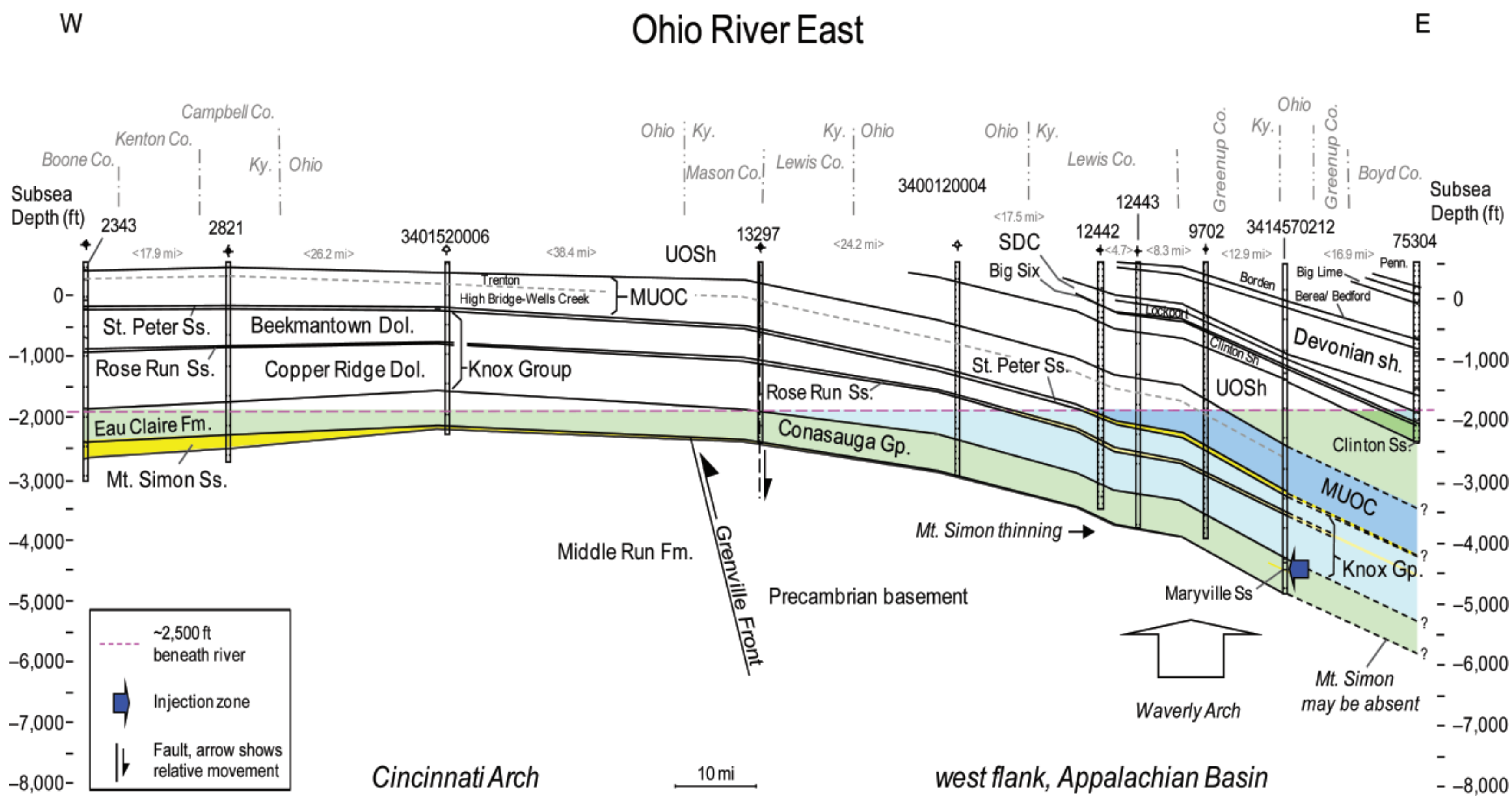

Figure 4.72. Ohio River (east) cross section showing intervals discussed in the "Rock Unit Summary." Intervals are color-coded according to their generalized carbon-storage category, as shown in Figure 4.5. Location of section shown in Figure 4.71. Wells used in this section are listed in Table 4.17. Expanded cross section with geophysical logs is shown in Plate 4.4. Faults that can be mapped at the surface are shown as solid at the top and dashed downward on the cross section. Faults that are not visible on the surface, but have been detected at depth from seismic analyses are shown as solid at the bottom and dashed upward in the cross section. MUOC=Middle–Upper Ordovician carbonate interval, SDC=Silurian–Devonian carbonate interval.

Table 4.17. Information on wells used for the Ohio River (east) cross section. Record numbers can be used to view well data in the KGS Oil and Gas Database.

Permit No.	*Record No.*	*Well Name*	*County*	*Elevation (ft)*	*Total Depth (ft)*	*Formation at Total Depth*	*Samples*
	2343	Ford 1 Conner	Boone	908	4,089	Middle Run Formation (Precambrian)	X
18051	2821	Ashland 1 Wilson	Campbell	747	3,604	Middle Run Formation (Precambrian)	X
	3401520006	Spencer Petroleum 1 Griffith	Brown, Ohio	947	3,348	Precambrian basement	?
3990	13297	United Fuel Gas 9061T Rawlings	Mason	764	3,314	Precambrian basement	X
	3400120004	Cabot 1-A Bailey A	Adams, Ohio	714	3,790	Precambrian basement	?
	12442	Thomas 1 Adams	Lewis	555	4,190	Precambrian basement	X
12443	12443	Ashland 1 Wolfe	Lewis	1,102	5,082	Precambrian basement	X
21256	9702	Commonwealth 1 Newel	Greenup	1,043	5,193	Precambrian basement	X
	341457	USS Chemicals/ US Steel No. 1 USS Chemicals	Scioto, Ohio	557	5,617	Precambrian basement	?
17627	75304	Inland Gas 528 Wolfe	Boyd	848	3,372	Clinton Siltstone (Silurian)	X

strata east and west of the fault, but does not appear to be associated with significant offset in overlying sedimentary strata (Fig. 4.72, Plate 4.4).

The Waverly Arch of Woodward (1961) is a north-south structure in northeastern Kentucky and southern Ohio that influenced Knox deposition, or at least erosion (see “Rock Unit Summary”). Numerous authors have placed the trend of the arch differently; Cable and Beardsley (1984) suggested that the arch migrated west through northeastern Kentucky through time in response to tectonic events on the eastern margin of the continent. In that scenario, Woodward’s (1961) location marks the position of the arch during Beekmantown (Early Ordovician) deposition and subsequent erosion along the Knox unconformity surface.

Precambrian Basement. The top of the Precambrian is not the top of crystalline basement everywhere along this section. In the western part of the section, Precambrian sediments (Middle Run Formation) fill a deep rift basin beneath the Cincinnati Arch (Drahovzal and others, 1992). The eastern margin of this structure is approximately the Grenville Front, a north–south-oriented thrust fault that separates Grenville volcanic basement rocks to the east from Precambrian Middle Run sedimentary and volcanic rocks to the west. East of the Grenville Front, the top of the Precambrian is basement, and varies from approximately 3,000 to more than 6,500 ft depth (Drahovzal and Noger, 1995). Immediately west of the front, the depth to basement is estimated to be more than 15,500 ft deep. A series of faults results in variable depth to basement westward, but on the western end of this section the depth to basement is approximately 8,500 ft.

Middle Run Formation. The top of the Precambrian Middle Run Formation is estimated to be approximately 3,000 ft deep on the Cincinnati Arch, based on seismic data, and deepens to the west. It does not extend east of the Grenville Front (Fig. 4.72, Plate 4.4). Based on seismic data, the Middle Run is estimated to be approximately 2,500 ft thick near the intersections of the Indiana, Kentucky, and Ohio state lines. It may reach thicknesses of more than 12,500 ft just west of the Grenville Front in Bracken County (Drahovzal and others, 1992). More than 1,900 ft of pre-Mount Simon sedimentary rocks (mostly sandstone and shale) were cored in Ohio's ODNR DGS No. 2627 borehole, approximately 40 mi north of the Kentucky border in Warren County, Ohio (Shrake and others, 1990, 1991). In Kentucky, only the uppermost part of the Middle Run Formation has been penetrated, but the sandstones and shales that were encountered showed little porosity. Basalts are interbedded with sandstones and shales in the Wilson well.

Mount Simon Sandstone. The Mount Simon is penetrated in most of the wells in this section, although it is labeled as a basal sand or Rome sand on drillers' logs in the area. The Mount Simon is at depths of 3,100 to 3,500 ft on the Cincinnati Arch, and deepens eastward. It is 3,430 ft deep in the Ford No. 1 Conner well, on the western end of the section, and is 270 ft thick (Fig. 4.72, Plate 4.4). Eastward the sandstone thins as it deepens. The Mount Simon is 44 ft thick in the Thomas No. 1 Adams well in Lewis County (depth of 4,110 ft) and 24 ft thick in the Commonwealth Gas No. 1 Newell well in Greenup County (depth of 5,063 ft). In the Thomas No. 1 Adams well, there was a show of gas in the sandstone (reported as basal sand) (Harris and Baranoski, 1996). In Scioto County, Ohio (across the river from Greenup County, Ky.), the Aristech Chemical No. 4 Aristech well encountered 70 ft of Mount Simon at 5,540 ft. The sandstone was reported to have 10 to 15 percent porosity. The sandstone may become arkosic to the east, which can make the interval look shaly on downhole gamma-ray logs. East and south, the sandstone pinches out.

A small-scale CO_2 injection demonstration test of the Mount Simon was completed in western Boone County (just west of the section) at the East Bend power station as part of the DOE-sponsored Midwest Regional Carbon Sequestration Partnership's regional phase II demonstration projects. More work is needed to determine if porosity zones in the East Bend well extend east as the unit thins.

Eau Claire–Conasauga Group. This interval is penetrated in all but the easternmost well along this section (Fig. 4.72, Plate 4.4). The Eau Claire Formation becomes the Conasauga Group eastward. Sandstones with potential porosity occur in the Conasauga, but not the Eau Claire. Sandstones in the Maryville Limestone of the Conasauga Group occur in Mason and Lewis Counties at depths of 2,500 to 2,800 ft (east of the Grenville Front). These sandstones were interpreted to have more than 4 percent porosity across at least a 20-mi stretch of the river, based on data from Ohio and south along the Kentucky River Fault System (Harris and others, 2004). A zone of sandy carbonates and sandstones in the United Fuel Gas No. 9061T Rawlings well (no. 13297 in Figure 4.72) is in the Maryville Limestone. Limestone with sandstone was reported at a depth of 3,180 to 3,190 ft, very sandy, friable dolomite from 3,200 to 3,210 ft, and sand and dolomite from 3,220 to 3,230 ft.

Gas shows have been reported from the Maryville (originally assigned to the Rome Formation) in the Aristech Chemical plant No. 4 well in Scioto County, Ohio (Ohio No. 3414570212). The Aristech well is east of the United Fuels Rawlings well and just across the river from Greenup County, Ky. (Harris and Baranoski, 1996). This well was an injection well for wastes from the Aristech Chemical plant. The Maryville was the injection reservoir at a depth of 5,198 ft.

The immediate confining interval for Maryville sandstones would be the overlying Maryville Limestone and the Nolichucky Shale, which thicken eastward into the Appalachian Basin (Plate 4.4). Along parts of the river where the Conasauga Group (especially the Nolichucky Shale) is more than approximately 2,500 ft deep, it would be the confining interval for any CO_2 injected into the underlying units. Westward, the Maryville thins and the Conasauga grades into shales of the Eau Claire Formation. The top of the Eau Claire is less than 2,500 ft deep on the crest of the Cincinnati Arch. Parts of the formation are deeper than 2,500 ft, but research would be needed to determine if adequate shale thickness remained for confinement of any underlying injection near the crest. Where the Eau Claire contains thick shales and is more than approximately 2,500 ft deep, it should provide adequate confinement for any CO_2 injected into the underlying Mount Simon in a supercritical state.

Lower Knox–Copper Ridge Dolomite. The Copper Ridge is penetrated in all but the easternmost well along this section (Fig. 4.72, Plate 4.4). At least parts of the Copper Ridge (lower Knox) are more than 2,500 ft deep across the Cincinnati Arch in the eastern part of the section, and the entire Copper Ridge is more than 2,500 ft deep east of the Lewis-Greenup County line. Numerous thin porosity zones are indicated in the Copper Ridge on geophysical logs, and represent either thin porosity intervals or discrete fractures. Several zones of sulfurous water, possibly associated with fractures, were noted in the upper Copper Ridge in the United Fuel Gas Co. No. 9061T Rawlings well at depths of 1,710 to 1,720 ft and 1,730 to 1,735 ft. Gas with H_2S was reported at 1,718 ft. How extensive any of these zones are to the east, where the unit is deeper is uncertain.

Rose Run Sandstone. The Rose Run is penetrated in all but the easternmost well along this section (Fig. 4.72, Plate 4.4). The sandstone is generally between 20 and 60 ft thick along this part of the Ohio River. It is thinnest in Mason County and thickest in Boone County. West of Mason County, the Rose Run is less than 2,500 ft deep. East of Mason County, the sandstone gradually deepens into the basin to more than 5,500 ft on the eastern end of the section (see “Rock Unit Summary”).

On the western end of the section, a sandstone was reported at depths of 2,150 to 2,210 ft (890 ft below the top of the Knox) in the Ford No. 1 Conner well. This is likely the Rose Run. The sandstone was described as poorly sorted, clean, and friable, with interbedded dolomite. Eastward, the sandstone was described as friable or unconsolidated in the United Fuel Gas Rawlings and Thomas Ralph N. No. 1 Adams wells. In the Thomas well, the Rose Run has an apparent porosity of 6 to 8 percent from 2,735 to 2,742 ft.

The United Carbon Co. No. 2992 Felty well in Greenup County (just south of the line of section) was abandoned when it filled up with 3,400 ft of water from a sandstone from 4,012 to 4,022 ft. Several attempts to bail, case, and cement the well were unsuccessful. Descriptions of cuttings from the interval indicate a dolomite with chert, shale, and some quartz grains. This appears to be the Rose Run. A zone of porosity that may be equivalent to this water-bearing interval was noted in two nearby wells. In the Commonwealth Gas Corp. No. 1 Newell well a 22-ft-thick porosity zone (2 to 4 percent) is at a depth of 3,675 ft, which is 162 ft below the top of the Knox. The Ashland Oil and Refining Co. No. 1 Wolfe well also had a relatively thick zone (22 ft) of porosity (8 to 10 percent) at a depth of 3,554 ft, which is 189 ft from the top of the Knox.

To the north in Ohio, porosity is best developed in the Rose Run where it pinches out updip against the unconformity at the top of the Knox. Although the Rose Run rises toward the unconformity along the eastern part of this section (along the Waverly Arch) in Greenup and Carter Counties, it is not truncated in Kentucky. Still, secondary porosity development from exposure of the overlying Knox above the Waverly Arch may explain porosity development in the Rose Run along this part of the river.

Upper Knox–Beekmantown Dolomite. The Beekmantown is penetrated in all but the easternmost well along this section (Fig. 4.72, Plate 4.4). The top of the Beekmantown is shallower than 2,500 ft across much of the section, but east of the Greenup-Lewis County line it is more than 2,500 ft deep. Along this stretch of the river, the unconformity at the top of the Knox truncates the upper part of the Beekmantown, causing the upper Knox to thin.

A gas show was reported in the upper 150 ft of the Beekmantown in the Ashland No. 1 Wolfe well, Lewis County. A gas show was also reported at a similar interval in the Inland Gas No. 535 McKeand well in Boone County, just south of the line of the cross section. In other wells along the section, several zones of water and possible porosity were noted, but these intervals are generally narrow and porosity is less than in the underlying Rose Run Sandstone (middle Knox). Some of the water and gas shows in the lower part of the Beekmantown along this stretch of the river may also be related to water and gas in the more porous Rose Run Sandstone beneath. On the western end of the section, in the Ford No. 1 Conner well, the hole filled with water (with a sulfurous odor) at a depth of 2,109 ft, which is 41 ft above the underlying Rose Run Sandstone.

St. Peter Sandstone. The St. Peter is penetrated in all but the easternmost well along this section, although its occurrence and thickness are highly variable. The sandstone is generally thin and shallower than 2,500 ft east of the Greenup-Lewis County line, and deepens to more than 5,000 ft in the Rome Trough (Fig. 4.72, Plate 4.4).

The St. Peter is reported as 60 ft thick (depth of 1,200 ft) in the Ford No. 1 Conner well, much thicker than in surrounding areas, but it is absent in other areas. In the United Fuels Rawlings well, the St. Peter is described as 75 ft thick at a depth of 1,400 ft, but is mostly dolomite with sand grains rather than thick sandstone. This indicates that the St. Peter is interbedded with the overlying Wells Creek carbonates along this part of the river. A local pod of St. Peter Sandstone as much as 20 ft thick occurs in parts of Lewis, Greenup, and Carter Counties. Where the St. Peter is dominated by carbonates, it is difficult to differentiate on downhole geophysical logs, which makes picking the top of the Knox difficult. It also suggests less likelihood for good porosity development.

Middle-Upper Ordovician Carbonates. This interval is penetrated in all but the easternmost well along this section (Fig. 4.72, Plate 4.4). The Lexington (Trenton) Limestone is near the surface on the western end of the section and deepens east to more than 3,000 ft in the Rome Trough. There is little porosity in the interval along this part of the river. A slight show of gas was recorded in the Wells Creek Formation (near the base of the interval) at depths of 3,662 to 3,670 ft in the United Carbon No. 2992 Felty well in Greenup County, toward the eastern end of the section.

Tuscarora (Clinton) Sandstone. The Tuscarora pinches out in the subsurface before the Silurian reaches the surface in Lewis County. It only occurs (and would only be deeper than 2,500 ft) in the extreme eastern part of the section (Fig. 4.72, Plate 4.4). The Tuscarora (drillers' Clinton) is an oil and gas target on the eastern end of the section in Boyd County. Gas was encountered in a 3-ft section of 28-ft-thick sandstone at a depth of 3,321 ft in the Inland Gas No. 528 Wolfe well. Several wells produce from the Clinton in Boyd County and across the river in neighboring West Virginia (Patchen, 1968b).

Keefer (Big Six) Sandstone. The Keefer pinches out or grades laterally into carbonates in the subsurface before the Silurian reaches the surface in Lewis County. It is less than 2,500 ft deep in all but the extreme eastern part of the section (Fig. 4.72, Plate 4.4) The Keefer (drillers' Big Six) has variable development (20 to 52 ft thick) beneath the eastern part of the Ohio River, but in the wells along this section has little apparent porosity. Two fields in Wayne County, W.Va., just across the river from Boyd County, Ky., produce from the Keefer at depths greater than 2,500 ft (Patchen, 1968a), so there may be potential for porosity in this interval in parts of Boyd County.

Silurian-Devonian Carbonates. Silurian-Devonian carbonates (drillers' Corniferous) are at the surface in Lewis County and are less than 2,500 ft deep in all but the extreme eastern part of the section (Fig. 4.72, Plate 4.4). The Inland Gas No. 528 Wolfe well (Boone County) had shows of gas and water in the Corniferous carbonates at depths of 2,579 to 2,978 ft from four thin zones. This same well had gas shows in the deeper Tuscarora Sandstone.

Devonian Shale. The Ohio Shale is at the surface in Lewis County, dips east to depths of more than 1,000 ft in Greenup County, and thickens to the east with depth (Fig. 4.72, Plate 4.4). The shale in this section is north of its main producing area in the Big Sandy Field of Pike and surrounding counties, so is unlikely to have the same potential here for enhanced gas production with CO_2 or unconventional CO_2 storage as farther to the south. For more information on the potential of the shale for carbon storage, see Nuttall and others (2005).

At depth, the Devonian shale would be considered a confining interval for underlying injection. Along this section, however, the shale is less than 2,500 ft deep and is likely shallower than needed to keep any CO_2 injected into underlying units in a supercritical state.

Shallower Porosity Horizons Deeper than 2,500 ft. Shallower reservoirs are unlikely along this line of section.

Coals Deeper than 1,000 ft. Coals are too shallow and thin along this section to be considered for coal storage or sequestration with enhanced coalbed methane production.

Ohio River (East) Summary. In the western part of the section, the Mount Simon Sandstone is the only possible unit for carbon storage at a depth of more than 2,500 ft. CO_2 injection in the sandstone was tested at Duke Energy's East Bend Station (just west of the section) in the summer of 2009. Initial results are promising, and reports from the test are pending. Eastward, the Mount Simon thins and may have less potential than it has to the west, although 70 ft of sandstone has been reported as far east as Scioto County, Ohio (across the river from Greenup County, Ky.). Eastward, there is potential for at least small-scale storage in the Rose Run Sandstone and a sandstone in the Maryville Limestone of the Conasauga Group. The Maryville was used as an industrial-waste injection reservoir at a depth of 5,198 ft at the Aristech Chemical site in Scioto County, Ohio. More information about this injection site is needed to assess this interval's potential storage capacity in neighboring parts of Kentucky. Several deep wells along the Waverly Arch have encountered porosity in the upper Knox and Rose Run Sandstone, which may indicate storage potential above that structure. In the easternmost part of the section, multiple thin porosity zones may be stacked above the Knox, in order to achieve greater cumulative thickness, but more research would be needed.

Green River

The Green River cross section extends from near the mouth of the river in Henderson County, south to Logan County (Fig. 4.63). Several fossil-fuel-powered electricity-generating facilities are along the river (Table 4.18), including TVA's Paradise station, the largest power plant in the state. Several additional plants have been proposed, including Cash Creek's (Erora-Emerald) Cash Creek station (1,000 MW) in Henderson County, Reliant Energy's Grane Creek station (500 MW) in Webster County, and Peabody Energy's Thoroughbred station (1,500 MW) in Muhlenberg County.

The Green River section is constructed from data from 22 wells (Figs. 4.73–4.74, Plate 4.5, Table 4.19). None of the wells reach basement, which is at great depths across the central part of the section. Drillers' descriptions of cuttings are available for the Texas Gas Kerrick well (below 3,705 ft).

Structures and Faulting. This cross section cuts across the Rough Creek Graben, a Cambrian failed rift (see "Rock Unit Summary"). Many of the intervals discussed in this report thicken and deepen into the graben. The northern boundary of the graben is the Rough Creek Fault System (RCF in Figure 4.74). Several of the deep wells in this section were drilled along the fault system to test potential structural and combination traps along the deeper, northern margin of the graben. The southern boundary of the graben is the Pennyrile Fault System (PFS in Figure 4.74) and an unnamed fault system south of the Pennyrile faults. Each of these systems has surface expression. At the surface, the graben-bounding fault systems consist of a complex series of splitting and reattaching faults, which sometimes merge into a single fault in the subsurface.

The graben is also cut by a series of northeast–southwest-oriented faults, informally called the Central faults. These faults bound a series of horsts and grabens. The intersection of several Central faults with the Rough Creek Fault System in McLean County leads to a great density of faults (spacing of more than one fault per mile) in that area (Fig. 4.74). A cross section by Noger and Drahovzal (2005) along the Rough Creek Fault System provides additional data for understanding the subsurface stratigraphy along the fault system east and west of the Green River. A cross section by Whitaker and others (1992) illustrates the complexity of faulting across the Rough Creek Graben, west of the Green River section.

Precambrian Basement. No wells have penetrated basement in this part of the state, so all estimates are based on seismic data. In the northern part of the section (eastern Henderson County), Precambrian basement is estimated to be 12,900 ft deep (12,500 ft below sea level). South of the Rough Creek Fault System, the depth to basement increases dramatically to more than 24,000 ft (see "Rock Unit Summary"). Farther south, the depth to basement shallows across a series of faults. On the southern end of the section in Logan County, the depth to basement is estimated to be 8,500 to 8,600 ft deep.

Mount Simon Sandstone. No wells have been drilled into the sandstone along this stretch of the river (Fig. 4.74, Plate 4.5), so all estimates are based on seismic data. Regional thickness trends suggest that the sandstone is less than 200 ft thick on the northern end of the section and thins to below detectable limits on seismic surveys north of the Rough Creek Fault System (see

Table 4.18. Electric-power-generating stations along the Green River. Data from Kentucky Public Service Commission (June 10, 2008) and Energy Information Administration (2006).

Owner	*Plant Name*	*Capacity (MW)*	*Fuel*	*County*
Western Kentucky Energy/Big Rivers	Henderson 2	365	coal	Webster
Western Kentucky Energy/Big Rivers	R.D. Green	528	coal	Webster
Western Kentucky Energy/Big Rivers	R.A. Reid station	99	fuel oil	Webster
Western Kentucky Energy/Big Rivers	R.A. Reid station	96	coal	Webster
Western Kentucky Energy/Big Rivers	D.B. Wilson	440	coal/coke	Ohio
Kentucky Utilities (E.ON)	Green River	189	coal	Muhlenberg
Tennessee Valley Authority	Paradise	2,558	coal	Muhlenberg

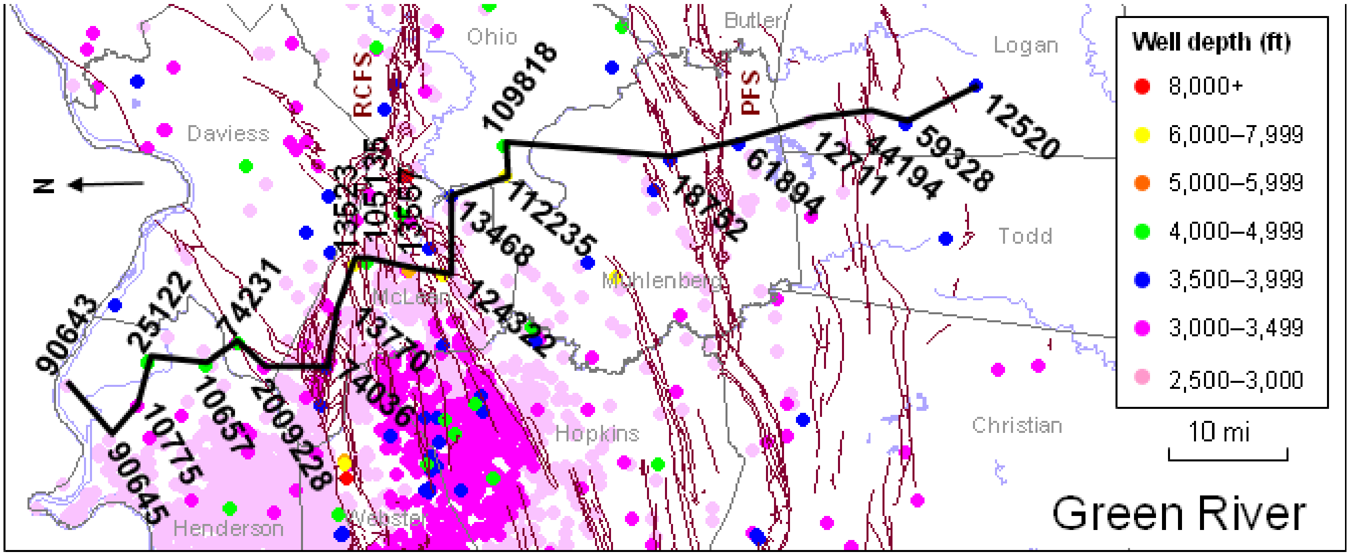

Figure 4.73. Location of the Green River cross section. Wells used in the section are labeled by their record number (see Table 4.19). Locations of other wells in the vicinity are color-coded for depth. Wells less than 2,500 ft in depth are not shown. The map is oriented east–west rather than north-south to better fit on the page. Faults exposed at the surface are shown as brown lines. PF=Pennyrile fault system, RCF=Rough Creek Fault System.

"Rock Unit Summary"). Even if the sandstone does occur on the northern end of the section, it would be deeper than 11,000 ft, which is well below the maximum depth (7,000 ft) for likely porosity development inferred by Hoholick and others (1984).

Eau Claire Formation. The Eau Claire is deeper than any drilling to date along this section. Based on seismic analysis, the top of the interval is estimated to be 12,900 to 13,000 ft deep north of the Rough Creek Fault System, 13,500 to more than 20,000 ft deep in the Rough Creek Graben, and 10,000 to 8,900 ft deep south of the graben. Deep strata in the graben, including the Eau Claire Formation, are currently being studied by the Kentucky Geological Survey's Rough Creek Graben Consortium. The Eau Claire is estimated to be 180 to 945 ft thick on the north end of the section, and more than 9,000 ft thick in the graben. Where it is unfaulted, it would likely provide an adequate seal to underlying injection if any deeper reservoirs are ever discovered.

Lower Knox–Copper Ridge Dolomite. The Knox Group is penetrated in several wells on the southern end of the Green River cross section (Fig. 4.74, Plate 4.5). The Rose Run Sandstone is missing in this area, so differentiating the Copper Ridge from the Beekmantown is difficult. Where the Copper Ridge is penetrated in these wells, it does not exhibit significant porosity. The Copper Ridge is estimated to be at depths of 7,000 to 9,000 ft north of the Rough Creek Fault System. It deepens to more than 9,000 ft south of the faults in the Rough Creek Graben (Noger and Drahovzal, 2005), and then gradually rises in elevation toward the southern end of the graben. In Logan County, south of the graben, the Copper Ridge is estimated to occur at depths of 3,500 to 5,000 ft.

In the Rough Creek Fault System, a 79-ft-thick porosity zone occurs in the Copper Ridge in the Texas Gas No. 1A Kerrick well at a depth of 7,380 ft. The net thickness of sandstone with greater than 4 percent porosity is 54 ft. Net thickness with more than 10 percent porosity is approximately 16 ft. Mean porosity based upon density logs is 9.3 percent (range of 4 to 17 percent). Mud cake is indicated across the porosity zone on the caliper log, and an invasion profile was recorded on the resistivity log, which indicates permeability as well. This well was 11 mi from Kentucky's proposed FutureGen site on the Green River in Henderson County, and this porosity zone was modeled as the primary reservoir (Commonwealth of Kentucky, 2006). If the porosity zone were laterally continuous and followed local structure, the injection plume for the FutureGen site would be estimated to encompass an area of 50.2 mi^2.

Gunter (Rose Run) Sandstone. The Rose Run does not occur this far west in Kentucky. A sandstone in Missouri and southern Illinois at the same stratigraphic

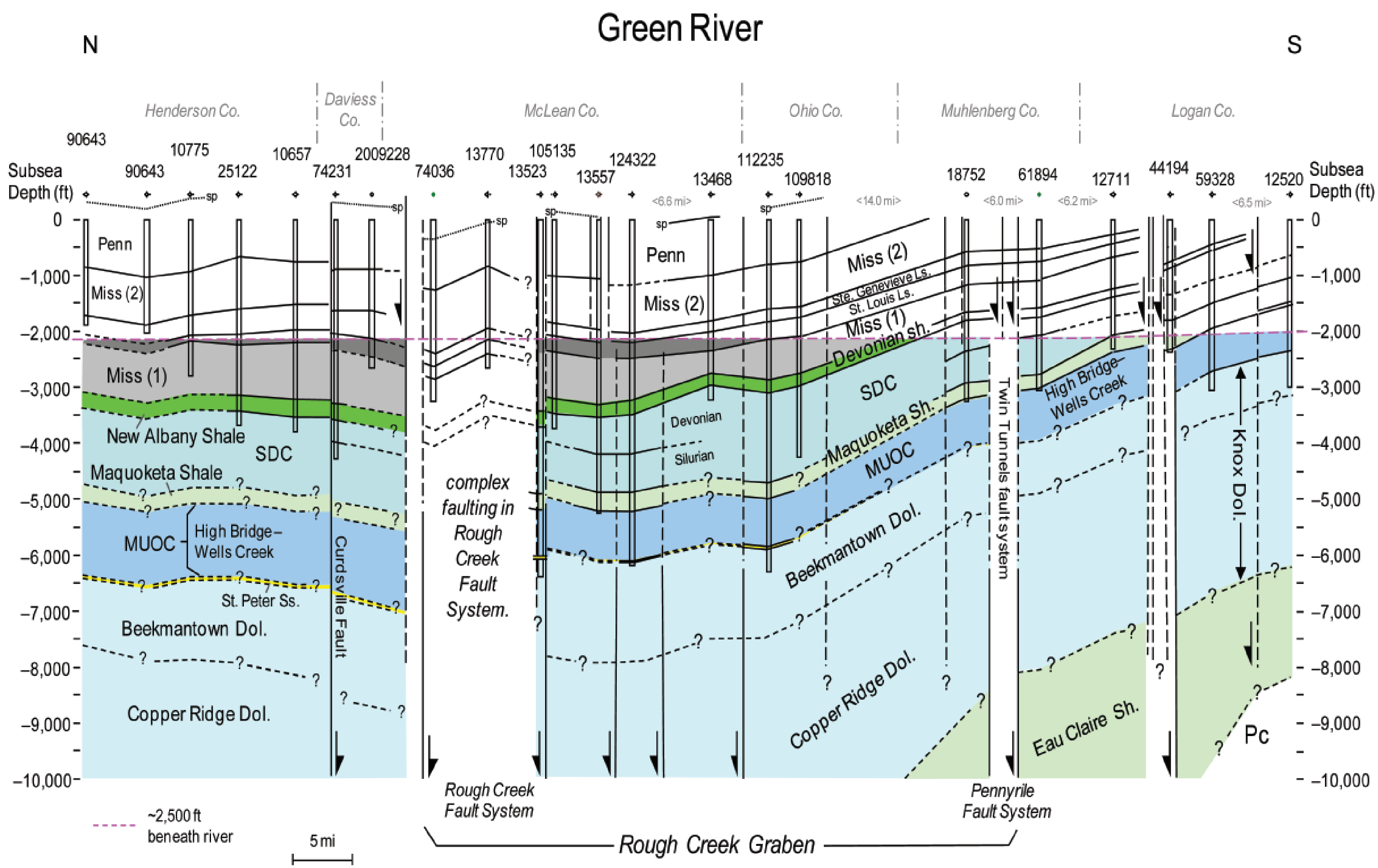

Figure 4.74. Green River cross section showing intervals discussed in the "Rock Unit Summary." Intervals are color-coded according to their generalized carbon-storage category as shown in Figure 4.5. Location of section shown in Figure 4.73. Wells used in this section are listed in Table 4.19. Expanded cross section with geophysical logs is shown in Plate 4.5. Faults that can be mapped at the surface are shown as solid at the top and dashed downward on the cross section. Faults that are not visible on the surface, but have been detected at depth from seismic analyses, are shown as solid at the bottom and dashed upward in the cross section. Surface faults connect to basement faults, but the level at which they connect or split is uncertain without specific data at that location. Because there are few deep wells along this section, there is significant uncertainty about the thickness and depth of the deeper units. MUOC=Middle–Upper Ordovician carbonate interval, Pc=Precambrian, SDC=Silurian–Devonian carbonate interval.

Table 4.19. Information on wells used for the Green River cross section. Record numbers can be used to view well data in the KGS Oil and Gas Database.

Permit No.	*Record No.*	*Well Name*	*County*	*Elevation (ft)*	*Total Depth (ft)*	*Formation at Total Depth*	*Samples*
	90643	Cherry & Kidd 1 Ohio	Henderson	372	2,250	Ste. Genevieve Limestone (Mississippian)	X
	90645	McCummings Oil 1A Dorsey	Henderson	479	2,511	Ste. Genevieve Limestone (Mississippian)	X
42739	10775	Quatro Oil 2 Casey	Henderson	424	3,222	Lower part of Mississippian	
33342	25122	Wiser 1 Ralph	Henderson	384	4,080	Middle part of Devonian	X
49878	10657	HAR-KEN Oil H1 King	Henderson	455	4,251	Clear Creek Formation (Devonian)	X
73979	74231	Jackson Invest. 1 Rafferty	Daviess	393	4,690	undifferentiated Silurian	X
24641	2009228	L&H Drilling 1 Snyder	Daviess	450	3,120	Warsaw Formation (Mississippian)	
34621	74036	KEN-TEX Oil 1 Young	McLean	415	3,671	Fort Payne Formation (Mississippian)	X
46625	13770	Falcon Petro 1 Kittinger	McLean	441	3,100	Salem/Warsaw Formation (Mississippian)	
17284	13523	Texas Gas 1A Kerrick	McLean	440	6,830	Knox Group (Ordovician)	X
82939	105135	William Laird 6 Walker	McLean	448	4,176	Clear Creek Formation (Devonian)	X
27281	13557	Tamarack Petro 3 Conrad	McLean	388	5,626	High Bridge Group (Ordovician)	X
93564	124322	Eastern American Energy 1-D Revlett	McLean	384	6,560	Knox Group (Ordovician)	
44892	13468	Empire Oil and Gas 1 Everly	McLean	398	3,630	Clear Creek Formation (Devonian)	
87030	112235	Refuge Exploration 2CU Hess	Ohio	382	6,700	Knox Group (Ordovician)	X
85868	109818	Refuge Exploration 1-3K30 Lewis	Ohio	462	4,715	Maquoketa Shale (Ordovician)	X
27937	18752	HAR-KEN Oil 5 Kirkpatricks	Muhlenberg	500	3,752	Clear Creek Formation (Devonian)	X
70199	61894	Coastline Oil and Gas 1 McElwain	Muhlenberg	556	3,624	Trenton Limestone (Ordovician)	X
	12711	Yingling 25 Diamond Springs	Logan	472	2,800	undifferentiated Ordovician	
64546	44194	Duke 1 Jernigan	Logan	510	2,885	undifferentiated Ordovician	
69443	59328	Houston 2 Mutual Benefit	Logan	629	3,700	Knox Group (Ordovician)	X

Table 4.19. Information on wells used for the Green River cross section. Record numbers can be used to view well data in the KGS Oil and Gas Database.

Permit No.	*Record No.*	*Well Name*	*County*	*Elevation (ft)*	*Total Depth (ft)*	*Formation at Total Depth*	*Samples*
27313	12520	Wiser 1 Markham	Logan	625	3,613	Knox Group (Ordovician)	X

level is called the Gunter Sandstone. The Gunter is not reported in the wells that penetrate the Knox on the southern end of the Green River cross section. Wells northward along this section are not deep enough to have penetrated the Gunter, if it occurs in that area. The Gunter was encountered in the Kentucky Geological Survey No. 1 Blan well in Hancock County (east of the section and north of the Rough Creek Fault System) and had good porosity. Reports on the Hancock County well are pending, but the occurrence of the Gunter to the east indicates it may occur along the northern part of the section. The Exxon Minerals No. 1 Duncan well of Webster County (west of this cross section) and the Texas Gas No. 1 Shain well of Grayson County (east of this cross section) both reported Gunter sandstones on top of the Copper Ridge. These wells were drilled along the northern margin of the Rough Creek Graben. Whether or not this sandstone is continuous between the wells or is confined within the graben is uncertain at this time. If it occurs in the graben, it would occur at depths of 6,500 to 9,000 ft, which might be deeper than optimal for porosity development, based on data from the Mount Simon and St. Peter Sandstones.

Upper Knox–Beekmantown Dolomite. The upper Knox is penetrated in six wells along the Green River section (Fig. 4.74, Plate 4.5). It is approximately 6,500 ft deep on the north end of the section, and deepens to between 6,500 and 7,000 ft in the Rough Creek Graben. South of the Pennyrile faults it shallows rapidly to depths of less than 3,000 ft. Neither water nor shows of oil or gas were reported in the Beekmantown along the section, although few wells penetrate the unit at depth, and saline water and significant hydrocarbons have been encountered updip on the eastern margin of the Illinois Basin.

St. Peter Sandstone. The St. Peter is penetrated in six wells along the Green River section (Fig. 4.74, Plate 4.5). It is approximately 6,500 ft beneath the surface on the northern end of the section, and deepens to between 6,500 and 7,000 ft in the Rough Creek Graben. South of the Rough Creek Fault System, the St. Peter thins and is interbedded with carbonates in the Wells Creek Formation. How far south the sandstone extends is uncertain. It appears to be missing south of the Pennyrile Fault System (PFS in Figure 4.74). Even where thick, the St. Peter shows little evidence of significant porosity. Depths of 6,500 to 7,000 ft would be predicted to have low porosity based on regional trends (see, for example, Hoholick, 1984).

Middle-Upper Ordovician Carbonates. This interval is penetrated in seven wells along the Green River section (Fig. 4.74, Plate 4.5). North of the Rough Creek Fault System, the Middle-Upper Ordovician carbonates are at depths of 4,500 to 5,000 ft. The interval shallows to less than 2,500 ft depth on the southern end of the section. Very little oil and gas has been produced and there is little evidence of significant porosity in the Middle-Upper Ordovician carbonates in western Kentucky, or for that matter in the southern part of the Illinois Basin (see, for example, Seyler and Cluff, 1988), so this would likely be considered a secondary confining interval for any deeper carbon storage.

Upper Ordovician Shale. None of the wells in the northern part of the section reach the Maquoketa Shale. Based on seismic analysis, it is 4,800 to 5,500 ft deep. Within the Rough Creek Graben the Maquoketa is penetrated in four wells and is typically 450 ft thick. It shallows from north to south from 5,100 to 3,500 ft deep. South of the graben it shallows to less than 2,500 ft deep, so it could not be used as a confining interval that would keep any CO_2 injected into underlying units in a supercritical state in that area. To the north, where it is unfaulted, the Maquoketa would likely provide an adequate seal to underlying injection (if suitable intervals are discovered).

Silurian-Devonian Carbonates and Sandstones. This interval is penetrated in 11 wells along the Green River section (Fig. 4.74, Plate 4.5). There has been very little oil and gas production or evidence of significant porosity in Silurian-Devonian carbonates in western Kentucky. Porosity is developed below the base of the shale in the Refuge Exploration Lewis well from 3,520 to 3,541 ft in the Sellersburg Limestone, however; a trace of oil was noted in the Jeffersonville Formation at 3,655 ft; and there was a very slight show of oil in the Dutch Creek Limestone at 3,648 ft. A drillstem test recorded slight gas from the Jeffersonville to Dutch Creek interval (3,486 to 3,726 ft) in this well. More work would be needed to determine if any of these intervals have enough porosity and permeability for carbon storage.

Devonian Shale. The shale is penetrated in nine wells along this section, mostly at either end of the section, where it is shallower (Fig. 4.74, Plate 4.5). In Henderson and Daviess Counties, north of the Rough Creek Graben, the shale is 250 to 300 ft thick beneath the Green River, at depths of 3,350 to 3,500 ft (Schwalb and Potter, 1978). Within the graben, the shale is 180 to 260 ft thick, and is thickest in northern Muhlenberg County. Just south of the Refuge Exploration Lewis well, the top of the shale is less than 2,500 ft deep. South of the graben, the shale thins (100 to 40 ft) and shallows from approximately 2,100 ft to less than 1,000 ft deep (Schwalb and Potter, 1978). There was a slight show of gas in the shale in the Refuge Exploration Lewis well from 3,395 to 3,425 ft. No gas has been produced from the shale in this part of the basin, however, so the use of CO_2 for enhanced gas production would be limited.

South of the Pennyrile Faults, the New Albany is shallower than 2,500 ft deep, so could not be used as a confining interval that would keep any CO_2 injected into underlying units in a supercritical state. Elsewhere, where the shale is unfaulted, it should be a good confining interval for large-scale injection in underlying reservoirs.

Shallower Porosity Horizons Deeper than 2,500 ft. Several Mississippian horizons are conventional oil and gas targets in the Green River area at depths below 2,500 ft. These horizons are not discussed in the "Rock Unit Summary" because (1) the area in which they occur at depths of more than 2,500 ft are relatively small and (2) they were shallower than the Devonian shale, which is a primary confining interval. They may offer small-scale injection possibilities or enhanced oil and gas opportunities as discussed in chapter 2 of this report. Summaries for known Mississippian porosity (oil and gas production) include field studies and overviews in Miller (1968), Zupann and Keith (1988), and Leighton and others (1991), as well as many Kentucky Geological Survey pool and field studies. Numerous oil and gas fields are in these horizons north of the Rough Creek Fault System at depths of less than 2,500 ft.

The Ken-Tex Oil No. 1 Young well, McLean County, is just south of the Rough Creek Fault System, and several Mississippian units are shallower than 2,500 ft elsewhere on the section are deeper than 2,500 ft in this well. A show of oil in otherwise nonporous Jackson sand of drillers' at 2,503 to 2,520 ft was reported. In addition, water was reported in the Cypress Sandstone at 2,560 to 2,593 ft, and in the McCloskey B zone (Ste. Genevieve Limestone) there was a very slight show of oil at 3,010 to 3,037 ft. The McCloskey (Ste. Genevieve) had shows of oil or water in several wells at less than 2,500 ft, including the Jackson Investment Rafferty well (2,335 to 2,355 ft), the Falcon Petroleum No. 1 Kittinger well (2,361 to 2,366 ft, 2,366 to 2,370 ft, 2,370 to 2,375 ft, and 2,375 to 2,383 ft), the Tamarack Petroleum Conrad well (2,458 to 2,471 ft), the Refuge Exploration Hess well (2,133 to 2,137 ft), the Refuge Exploration Lewis well (2,167 to 2,173 ft, 2,193 to 2,197 ft, and 2,204 to 2,214 ft), and the Coastline McElwain well (1,130 to 1,170 ft).

The Har-Ken Kirkpatricks well was an injection well into the McCloskey. Initial production was 800 ft of water and 100 ft of oil at 2,115 to 2,119 ft, and 265 ft of gas and 50 ft of sulfur-smelling water at 2,127 to 2,135 ft. In the Tamarack well, Mississippian porosity was also noted in the St. Louis Limestone from 2,704 to 2,710 ft and the Salem/Warsaw Limestone at 2,862 to 2,882 ft, but the extent of those zones cannot be determined at this time.

Several large Mississippian oil and gas fields shallower than 2,500 ft occur in the vicinity of the Green River, including the Birk City Consolidated, Euterpe Consolidated, Curdsville Consolidated, Sebree Consolidated, Pratt Consolidated, and Guffie Consolidated. All have had secondary recovery and are discussed in chapter 2 of this report.

Coals Deeper than 1,000 ft. In and just south of the Rough Creek Fault System in southern Daviess and McLean Counties (between the L&H Drilling and Falcon Petroleum wells), coals beds occur at depths of more than 1,000 ft (upper part of Pennsylvanian in Figure 4.74, Plate 4.5). Most of the current DOE-sponsored coal-sequestration research considers 1,000 ft a minimum depth for CO_2 sequestration in coal beds or enhanced coalbed-methane recovery using CO_2, in order to ensure containment and to be below typical mining depths. In western Kentucky, the minimal depth might have to be increased in areas where the Springfield coal (W. Ky. No. 9) occurs at depth, because it is mined at depths in excess of 1,000 ft in at least one mine. Other western Kentucky coal beds are not mined underground at these depths.

In the Ken-Tex Young well, the Davis (W. Ky. No. 6) coal bed of the Carbondale Formation and deeper coals of the Tradewater Formation are more than 1,000 ft below the surface. Coalbed methane has not been produced from these beds, so CO_2 could not definitely be used for enhanced coalbed methane production, but future production with CO_2 cannot be discounted. Ongoing research concerning the use of coal beds for carbon storage will help in future evaluations of coal beds in the basin.

Green River Summary. Several parts of the Green River section cross areas with high concentrations of faults that would likely have to be investigated to determine if they are sealing or pathways for leakage prior to any large-scale injection project. The Mount Simon is thin, restricted to the area near the river's mouth, and is likely too deep for carbon storage. Likewise, the St. Peter Sandstone is at depths where it is likely to have little porosity, and it is nonporous where it has been penetrated. The lower Knox Group may have possibilities for carbon storage. A thick porosity zone was noted in the Copper Ridge in the Texas Gas Kerrick well. Too few deep wells are in this area to determine the actual extent of the porosity zone, however. Use of the Knox for large-scale storage would likely require stacking of multiple porosity zones or openhole completions within the Knox.

Mississippian strata may offer possibilities for at least small-scale storage, where they are deeper than 2,500 ft south of the Rough Creek Fault System, or for stacked storage of multiple relatively thin horizons in order to increase the net storage capacity. Mississippian reservoirs, however, are targets for oil and gas exploration and locally may have many well penetrations that would have to be considered as potential pathways for leakage in any injection project. Possibilities for some of the larger fields with existing secondary recovery in the area are discussed in chapter 2 of this report.

Cumberland River (and Lake Cumberland)

The Cumberland River cross section extends from near the Barren-Metcalfe County line east to Casey County and then southeast to Pine Mountain in Bell County (Fig. 4.63). Large towns in the area are Somerset, London, Corbin, and Pineville. Two fossil-fuel power plants are along the river (Table 4.20).

The Cumberland River section is constructed from data from 14 wells (Figs. 4.75–4.76, Plate 4.6, Table 4.21). Seven wells penetrate the Knox Formation, and four reached total depth in Precambrian basement. Samples for nine of the wells are filed at the KGS Well Sample and Core Library. Sample descriptions are also available for the entire extent of three of the wells at the KGS online Oil and Gas Database: the Benz Oil No. 1 Nunnally, Cities Service A1 Garrett, and United Fuel No. 8801A Knuckles. Sample descriptions are available for the shallow parts of two others: the Ashland No. 1 Tartar and Amerada Hess No. 1 Daulton.

Much of the section straddles the Cincinnati Arch, whose apex is located just west of the Ashland Oil and Refining Inc. No. 1 Tartar well in Casey County (Fig. 4.76, Plate 4.6). Eastward, strata dip into the Appalachian Basin. In general, strata west of the apex of the arch have a shallow westward dip, and strata east of the apex have a greater eastward dip. Surface rocks along the apex consist of Ordovician, Silurian, and Devonian strata. Eastward, Pennsylvanian strata of the Eastern Kentucky Coal Field occur at the surface, and the top of the Devonian Ohio Shale descends to a depth of more than 3,200 ft.

Structures and Faults. Several faults occur along the line of section (Figs. 4.75–4.76, Plate 4.6). The Goose Creek faults are a series of closely spaced, relatively north–south-oriented faults in Russell County. They are mapped at the surface on the Eli (Thaden and Lewis, 1965) and Russell Springs (Lewis and Thaden, 1965) geologic quadrangle maps, but what happens to the faults in the deep subsurface is uncertain. The

Table 4.20. Electric-power-generating stations along the Cumberland River in Kentucky. Data from Kentucky Public Service Commission (June 10, 2008) and Energy Information Administration (2006).

Owner	*Plant Name*	*Capacity (MW)*	*Fuel*	*County*
East Kentucky Power Cooperative	J.S. Cooper	344	coal	Pulaski
Kentucky Utilities (E.ON)	Pineville	38 (inactive)	coal	Bell

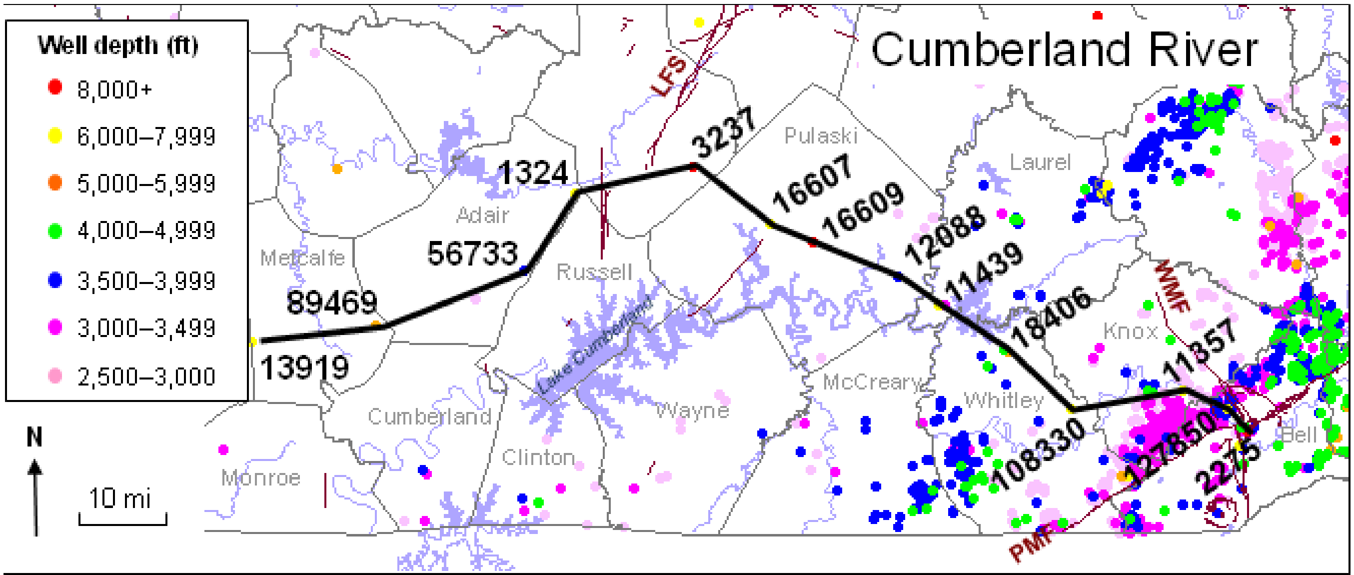

Figure 4.75. Location of the Cumberland River cross section. Wells used in the section are labeled by their record number (see Table 4.21). Locations of other wells in the vicinity are color-coded for depth. Wells less than 2,500 ft in depth are not shown. Faults exposed at the surface are shown as brown lines. GCF = Goose Creek faults. LF = Lexington Fault System. MS = Middlesboro structure. PMF = Pine Mountain Thrust Fault. RFF = Rocky Face Fault. WMF = White Mountain Fault System (includes Dorton Branch faults near Pine Mountain).

nearby Lexington Fault System is a basement system that parallels the crest of the Cincinnati Arch. The surface expression of these faults starts near the Cumberland River and continues north. The Grenville Front continues south in the subsurface. The Lexington Fault System is the shallower expression of the deep-seated Grenville Front. Offset along the Lexington-Grenville faults is down to the east with less than 1,000 ft of displacement of the Precambrian along this section of the fault (Drahovzal and Noger, 1995). The Lexington-Grenville fault defines the western border of the Rome Trough. The trough was subsiding during pre-Knox time, so the trough has greater thickness of pre-Knox strata. Several basement faults have been mapped using seismic analysis (Drahovzal and Noger, 1995) and they significantly influenced pre-Knox sedimentation within the trough. The southeastern boundary of the Rome Trough is the Rockcastle River Fault, which is located beneath Whitley County along this line of section. It has 2,000 ft of offset to the west at basement, but does not have surface expression, and may not have greatly influenced post-Knox sedimentation.

Just north of Pine Mountain in Bell County, the Nami Resources Inc. LLC No. 21 Lewis Heirs well is near the White Mountain Fault System (WMF in Figure 4.75). These faults are a series of northwest–southeast-oriented normal faults rooted in the basement. Overall offset at the basement is 500 to 600 ft (Drahovzal and Noger, 1995). The faults intersect another series of similarly oriented faults, called the Dorton Branch faults, in front of (northwest of) the leading edge of the Pine Mountain Thrust Fault.

The Pine Mountain Thrust Fault (PMF in Figure 4.75) occurs between the Nami Resources well and the easternmost well on the cross section. The Pine Mountain Thrust Fault is developed in the Devonian (Chattanooga/Ohio) shale and curves toward a horizontal attitude in the subsurface within the shale. It does not continue into the basement, so strata beneath the thrust are not offset. Strata above the Devonian shale on the southeastern side of the fault have been pushed up and over strata on the northwestern side of the fault. The thrust produces repeated section in the Devonian shale from 3,000 to 3,200 ft in the United Fuel Gas Co. No. 8801A Knuckles well in Bell County, southeast of Pine Mountain. A good cross section depicting details of the thrust fault and the White Mountain faults is shown on the Pineville geologic quadrangle map (Froehlich and Tazelaar, 1974).

Several other structural features influence strata on the Pine Mountain Thrust Block. The Rocky Face Fault (RFF in Figure 4.75) is a strike-slip or tear fault on the Pine Mountain Thrust Block. It is oriented similarly to the Dorton Branch faults on the northwestern side of the thrust. The Rocky Face Fault overlies an unnamed basement fault, which has 500 to 600 ft of

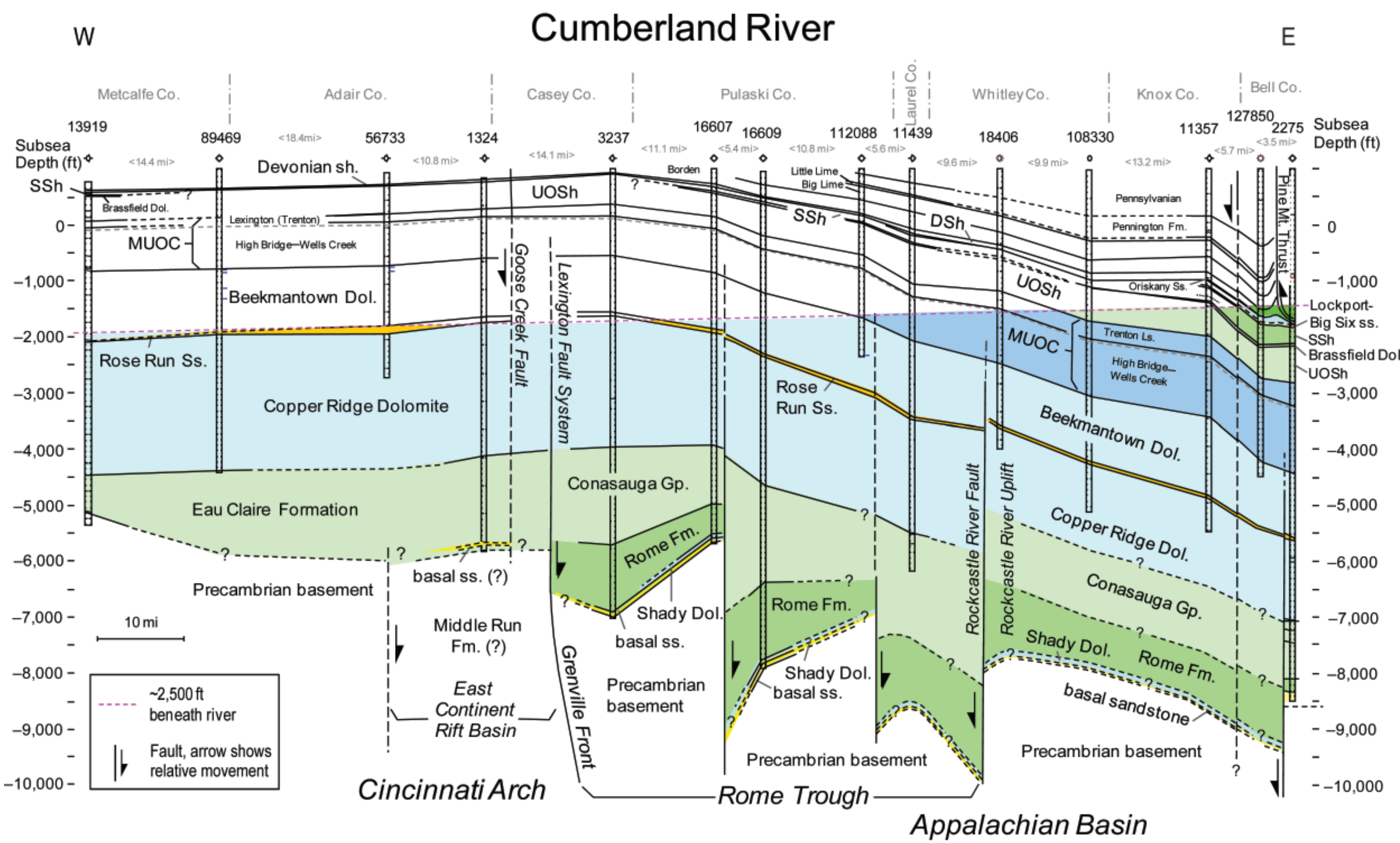

Figure 4.76. Cumberland River cross section showing intervals discussed in the “Rock Unit Summary.” Intervals are color-coded according to their generalized carbon-storage category as shown in Figure 4.5. Location of section shown in Figure 4.75. Wells used in this section are shown in Table 4.21. Expanded cross section with geophysical logs is shown in Plate 4.6. Faults that can be mapped at the surface are shown as solid at the top and dashed downward on the cross section. Faults that are not visible on the surface, but have been detected at depth from seismic analysis, are shown as solid at the bottom and dashed upward in the cross section. Surface faults connect to basement faults, but the level at which they connect or split is uncertain without specific data at that location. Basement depths and configuration of fault blocks based on data from Drahovzal and Noger (1995) and Harris and others (2004). MUOC=Middle–Upper Ordovician carbonate interval. SDC=Silurian–Devonian carbonate interval.

Table 4.21. Information on wells used for the Cumberland River cross section. Record numbers can be used to view well data in the KGS Oil and Gas Database.

Permit No.	*Record No.*	*Well Name*	*County*	*Elevation (ft)*	*Total Depth (ft)*	*Formation at Total Depth*	*Samples*
16717	13919	Benz Oil 1 Nunnally	Metcalfe	757	6,114	Precambrian basement	X
77972	89469	G&R Oil 1 England	Metcalfe	1,072	5,500	Conasauga Formation (Cambrian)	
68554	56733	Formula Drilling 1 Dalton	Adair	943	3,671	Copper Ridge Dolomite (Cambrian)	
14479	1324	Ashland 1 Tarter	Adair	850	6,677	basal sandstone (Cambrian)	X
34578	3237	Cities Service A1 Garrett	Casey	1,220	8,251	Precambrian basement	X
22670	16607	Amerada Hess 1 Daulton	Pulaski	1,043	6,722	Precambrian basement	X
22393	16609	Amerada Hess 1 Edwards	Pulaski	946	8,868	Precambrian basement	X
86944	112088	Alamco Inc. 6086 Snell/Hoffman	Pulaski	1,177	3,525	Knox Group (Ordovician)	X
20438	11439	Howard 3 Cumberland	Laurel	1,160	7,343	Rome Formation (Cambrian)	X
53298	18406	Delta-Mike 1 Ohler	Whitley	1,165	5,160	Copper Ridge Dolomite (Cambrian)	X
84852	108330	Alpha Gas 1 Cobb	Whitley	975	6,092	Copper Ridge Dolomite (Cambrian)	X
21553	11357	Petroleum Exploration 2 Carnes	Knox	1,050	6,523	Copper Ridge Dolomite (Cambrian)	
96688	127850	NAMI Resources 21 Lewis	Bell	1,769	6,263	Knox Group (Ordovician)	
964E9	2275	United Fuel 8801A Knuckles	Bell	1,491	10,034	basal sandstone (Cambrian)	X

offset to the southwest (Drahovzal and Noger, 2002). The Middlesboro structure (MS in Figure 4.75), which is south of the cross section, is a circular ring of faults, possibly formed through an ancient meteorite impact.

Precambrian Basement. Precambrian rocks are encountered in four wells beneath the Cumberland River (Fig. 4.76, Plate 4.6). Basement is shallowest on the western side of the section at a depth of 5,884 ft in the Benz Oil Corp. No. 1 Nunnally well. Based on seismic interpretations, the top of the Precambrian varies from approximately 5,000 to more than 11,500 ft depth in the area east of the Lexington Fault System in Russell County to Pine Mountain in Bell County (Drahovzal and Noger, 1995). As in other parts of the Cincinnati Arch, however, the top of the Precambrian does not delineate the top of crystalline basement everywhere. Basement is interpreted to occur at depths of more than 22,500 ft in the southernmost projection of the East Continent Rift Basin in central Pulaski County. In this area, the rift basin is approximately 10 mi wide. It is bounded on the west by rocks of the Granite-Rhyolite Province and to the east by the Grenville Front and granitic rocks of the Grenville Province. In the Amerada Petroleum Corp. No. 1 Edwards well in Pulaski County, basement is at a depth of 8,834 ft below the surface (7,922 ft below sea level).

Middle Run Formation. There may be more than 22,500 ft of Middle Run Precambrian sedimentary rocks in the narrow projection of the East Continent Rift Basin in Pulaski County, based on gravity and magnetic data (Fig. 4.76, Plate 4.6) (Drahovzal and others, 1992). The top of the Middle Run is estimated to be at approximately 6,500 ft depth in this area. No wells penetrate the Middle Run along this section, although a “granite wash” was reported at the bottom of the Ashland No. 1 Tartar well (6,658 to 6,677 ft), which may be reworked Middle Run.

Basal Sandstone. Basal sandstones are penetrated in three wells within the Rome Trough and a third well west of the Rome Trough. These sands may be continuous between wells, but this is uncertain. The basal sandstones vary from depths of 6,300 to more than 11,000 ft along this section. Variation in depth is a function of faulting within the Rome Trough, and the eastward dip of strata into the Appalachian Basin (Fig. 4.76, Plate 4.6). A sandstone reported as a basal sandstone in the United Fuels Knuckle well on the eastern end of the section is actually in the Rome Formation (Harris and others, 2004).

On the western end of the section, a sandstone is reported near the base of the Ashland No. 1 Tartar well (no. 1324 in Figure 4.76, Plate 4.6). The sandstone is 76 ft thick at depths of 6,471 to 6,547 ft. This is at least 130 ft above the Precambrian (the well did not reach total depth in basement, but may be in reworked Middle Run Formation). This sandstone is far south of the apparent pinchout of the Mount Simon Sandstone and west of the Lexington Fault System, which traditionally is thought to be the western border of sandstones in the Rome Formation (see "Rock Unit Summary"). The well is located west of the Goose Creek faults, so this area might represent a westward extension of the Rome Trough or a small fault block on the margin of the trough. If so, these sands could represent sandstones within the Rome Formation or basal sandstones similar to those encountered in wells to the east within the trough. Stratigraphically, the base of the sands in the Ashland well are near the base of the Conasauga Formation within the trough to the east, so these sandstones could also be in the lower Eau Claire or Conasauga Formations. More work is needed to correlate these sands, but for now they are included as basal sands of uncertain origin and extent. The gamma ray-neutron log for this well indicates several sandstones and shales from 6,492 to 6,578 ft, but individual sandstones are mostly less than 15 ft thick, and appear tight.

Eastward, in the Rome Trough, the basal sandstone is penetrated in three wells. It occurs from 8,004 to 8,116 ft in the Cities Service well, 8,760 to 8,833 ft in the Amerada Hess Daulton well, and from 6,625 to 6,713 ft in the Amerada Hess Edwards well. In each well, the entire thickness of the interval is not sandstone; rather, it consists of interbedded sandstones, siltstones, and shales. Most individual sandstones are less than 20 ft thick, and all appear to lack porosity. Sample descriptions from the Cities Service A1 Garrett well reported 10 ft of fine- to medium-grained white sandstone above a thicker section of shales and arkoses (red sandstones) of variable thickness.

Rome Formation. The Rome Formation is developed in the Rome Trough, in the central part of the section (Fig. 4.76, Plate 4.6). It is penetrated in four wells beneath the Cumberland River. In this part of Kentucky, the Rome is dominated by shale with interbedded carbonates, siltstones, and thin sandstones. Thick sandstones that occur to the north are mostly absent in this region (Harris and others, 2004). The thickest Rome sands along this section are in the United Fuel Gas Co. No. 8801A Knuckles well. In this well, two intervals of sandstone (9,828 to 9,840 and 9,860 to 10,034 ft) are separated by shale. Descriptions from samples indicate a fine- to coarse-grained, angular to subrounded, kaolinite- and quartz-cemented sandstone, interbedded with shale, limestone, dolomite, and rare glauconite. Little porosity is indicated in the geophysical logs. These sands were reported as basal sands in the driller's report, but Harris and others (2004) included them in the Rome.

Westward, a shaly sandstone is developed from 6,920 to 7,320 ft in the Cities Service Oil Co. A No. 1 Garrett well in Casey County. There was a slight show of gas in a thin, fine- to medium-grained sandstone at 7,210 ft and a very slight show of gas in a thin sandstone at 7,285 to 7,286 ft. There was also a slight show of gas in a shaly interval of the Rome at 7,470 ft. In the same well, another sandstone is toward the base of the Rome at a depth of 7,730 to 8,010 ft. Descriptions of cuttings indicate that it is a very fine- to medium-grained, poorly sorted, white to green, micaceous sandstone. Density logs show little porosity. This sandstone is underlain by an arkosic unit at depths of 8,010 to 8,150 ft. The arkosic unit also contains some quartzose sandstones, with some gray shale and a fine micaceous to clayey matrix. The arkosic unit has little porosity development.

Eau Claire–Conasauga Group. Eight wells reach this interval along the section, and five penetrate the entire interval (Fig. 4.76, Plate 4.6). The Eau Claire Formation becomes the Conasauga Group east of the Lexington Fault System in the Rome Trough. In northeastern Kentucky, sandstones with potential porosity have been documented in the Conasauga, but not along this part of the river, and not westward in the Eau Claire.

On the east end of the section, the top of the Eau Claire is approximately 5,200 ft deep and 605 ft thick. Most of the unit is dominated by shale. The interval thickens eastward toward the Rome Trough. The equivalent Conasauga Group is more than 1,500 ft thick and deepens from 4,500 to 8,000 ft eastward. Where the unit is unfaulted and shale-dominated, it would likely provide an adequate seal to underlying injection in basal or Rome sandstones, if any are ever discovered.

Lower Knox–Copper Ridge Dolomite. The lower Knox is penetrated in 11 of the wells in the Cumberland River section. The top of the Copper Ridge ranges in depth from approximately 2,400 ft on the Cincinnati Arch to 7,175 ft on Pine Mountain. The top of the Copper Ridge is at depths of less than 2,500 ft from Pulaski County westward. The Copper Ridge varies in thickness from 1,950 to more than 2,500 ft (Fig. 4.76, Plate 4.6). The Rose Run Sandstone, which is used to separate the Beekmantown Dolomite (upper Knox) from the Copper Ridge Dolomite (lower Knox), is poorly developed in this part of the state, so it is difficult to accurately pick the top of the Copper Ridge (lower Knox) in several wells.

Across much of the section the Copper Ridge is dominated by dense dolomite with little or no porosity, although local thin porosity zones (likely fractures) were noted in descriptions from several wells. The Cities Service Oil Co. A No. 1 Garrett well in Casey County had a gas show in a thin porosity zone in the Copper Ridge at 4,737 ft, which is 431 ft above the base of the unit. Drillstem tests were performed in the Copper Ridge in the Amerada Hess Corp. No. 1 Dalton well and Amerada Petroleum Corp. No. 1 Edwards well in Pulaski County, and the Howard Sober Inc. No. 3 Cumberland Minerals well in Laurel County. Data from these tests are shown in Table 4.22. No formation pressure information was reported for the Pulaski County tests, although water analyses were. Pressures were reported for the Laurel County tests, but formation water was not analyzed.

In Pulaski County, the shallower test in the Amerada Hess Corp. No. 1 Dalton well included a possible fracture at 4,530 ft (436 ft above the base of the unit) on the neutron and compensated formation density logs, and a low-resistivity zone beneath the possible fracture from 4,533 to 4,556 ft. The deeper test showed an apparent fracture at 4,784 ft on the FDC (compensated formation-density) log (182 ft from the base of the unit). In the Howard Sober Inc. No. 3 Cumberland Minerals well in Laurel County, four drillstem tests were attempted, but one failed. For the 5,005- to 6,085-ft test (largest interval), 3,135 ft of fresh water and 720 ft of gas-cut salt water were reported.

Rose Run Sandstone. The Rose Run Sandstone is absent or poorly developed along this section (Fig. 4.76, Plate 4.6). The stratigraphic position is penetrated in 12 wells. The unit is picked on several logs, and is shown in the cross section as Rose Run (in quotation marks) where it was picked, because in many cases it may not be a sandstone. Available sample descriptions from several of the wells indicate that the interval is dominated by dolomite with scattered sand grains and chert, rather than by sandstone. In the G&R Oil Corp. Inc. No. 1 England well, Metcalfe County, the well lost circulation at a depth of 2,850 ft, which would be approximately 1,071 ft from the top of the Knox at this location. A narrow porosity zone, which is likely a fracture, is at approximately this depth on the density log. This would be stratigraphically in or just above the Rose Run. Elsewhere, the interval shows little evidence of porosity along this section.

Upper Knox–Beekmantown Dolomite. The Beekmantown Dolomite extends across the entire section (Fig. 4.76, Plate 4.6). The top of the Beekmantown (top of the Knox) is 1,440 ft deep on the Cincinnati Arch, and deepens to more than 5,500 ft on Pine Mountain. It is at miscible depths (more than 2,500 ft) east of eastern Pulaski County. Several of the well records indicate water in the upper Knox, and logs commonly show thin porosity zones, which may be related to fractures, in otherwise thick sections of dense dolomite. Salt water was reported from four zones in the Beekmantown in the G&R Oil Corp. Inc. No. 1 England well, Metcalfe County (106, 151, 416, and 606 ft from the top, as reported by the driller). As previously mentioned, the well lost circulation 1,071 ft from the top of the Knox, which would be at the base of the Beekmantown, or in the Rose Run equivalent. In the Formula Drilling Inc. No. 1 Dalton well, Adair County, small amounts of water were noted at 1,695 to 1,700 ft (within 10 ft of the top of the Knox), and a large volume of water that "jammed [the] hammer" was reported at 1,765 to 1,770 ft (80 ft from the top of the Knox).

Oil shows from the Beekmantown were noted on geophysical logs in the Petroleum Exploration Co. No. 2 Carnes Heirs well, Knox County, at depths of 4,506 and 4,515 ft (within 20 ft of the top of the Knox), but were not reported on the driller's ticket, so may not

Table 4.22. Data reported from drillstem tests in the Copper Ridge Dolomite.

Permit No.	*Depth (ft)*	*Total Dissolved Solids (mg/L)*	*pH*	*Density*	*Initial Closed-In Pressure*	*Initial Flowing Pressure*	*Final Flowing Pressure*	*Final Closed-In Pressure*	*Final Hydrostatic Pressure*
22670	4,502–4,592	32,600	6.7	1.023	none	none	none	none	none
22670	4,700–4,790	42,500	6.8	1.030	none	none	none	none	none
22393	4,845–5,000	119,000	6.0	1.081	none	none	none	none	none
20438	5,005–6,085	none	none	none	2,070	1,480	1,721	1,957	2,073
20438	6,195–6,275	none	none	none	none	181	184	1,615	2,983
20438	6,500–6,580	none	none	none	none	26	181	2,287	3,145

be valid. Two drillstem tests were reported from this well at depths of 4,988 to 5,188 ft (490 to 690 ft from the top of the Knox). The first test was open 2 hr and reported 1,980 ft of gas; the second was open for 11 hr and reported 2,100 ft of gas. A notation on the geophysical log indicates a gas and oil show with sulfur at 4,992 ft (which is in the interval tested). Possible fractures are indicated on the geophysical logs at depths of 5,084 to 5,088 ft and 5,120 to 5,125 ft in the test interval. Eastward, in Bell County on Pine Mountain, the upper Knox had gas shows at 6,098 ft (158 ft from the top of the Knox) and oil shows at 6,370 to 6,390 ft (450 ft from the top of the Knox) and 6,880 to 6,884 ft (944 ft from the top of the Knox). The Knox is approximately 2,700 ft beneath the Pine Mountain Thrust at this location.

St. Peter Sandstone. The St. Peter Sandstone is absent in this part of the state.

Middle-Upper Ordovician Carbonates. The Trenton–Black River carbonate section is penetrated in all wells in this section (Fig. 4.76, Plate 4.6). It occurs at 500 ft on the Cincinnati Arch and deepens east to 4,300 ft east of Pine Mountain. This interval is dominated by dense limestones and dolostones. The top of the Trenton (Lexington) Limestone is at miscible depths (more than 2,500 ft) east of Whitley County. In the Alpha Gas Development Inc. No. 1 Cobb well, Whitley County, gas was produced after acid application at a depth of 2,580 to 2,586 ft, which is just above the Trenton (Lexington) Limestone in an interval of interbedded limestone and shale. A gas show was reported from a similar interval just above the Lexington Limestone at shallow depths of 585 to 592 ft in the Benz Oil Corp. No. 1 Nunnally well in Metcalfe County. No other water or hydrocarbons were reported from wells in this section.

Upper Ordovician Shale. The Upper Ordovician shale interval is penetrated by all of the wells along this section (Fig. 4.76, Plate 4.6). On the western end of the section, the Kope and Clays Ferry Formations consist of interbedded limestone and shale. The interval appears to get shalier to the southeast. It is more than 2,500 ft deep only on the eastern end of the section in parts of Knox and Bell County. Hence, it could not be used as a confining interval that would keep any CO_2 injected into underlying units in a supercritical state along most of the river.

Tuscarora (Clinton) Sandstone. Silurian strata are truncated from Pulaski County westward beneath the sub-Devonian shale unconformity (Fig. 4.76, Plate 4.6). A gas show was reported from the Silurian Tuscarora (Clinton) at a depth of 3,588 ft in the United Fuel Gas Co. No. 8801A Knuckles well in Bell County. The Tuscarora is likely too thin and laterally restricted to be a large-scale sequestration target, but if porosity is discovered in wells in Bell County, thin sandstones might be used with other deeper reservoirs in a stacked-reservoir scenario to increase net thickness and storage volume.

Silurian Shale. The Silurian Rose Hill (Clinton) Shale is truncated beneath the sub-Devonian shale unconformity in Pulaski County. Eastward, it thickens to more than 300 ft in Bell County (Fig. 4.76, Plate 4.6). The shale should have good confining characteristics where it is thick and more than 2,500 ft deep on the east end of the section.

Keefer (Big Six) Sandstone. The Keefer is not well developed along this section, and its stratigraphic position (beneath the Lockport Limestone) is truncated beneath the sub-Devonian shale unconformity west of Knox County (Fig. 4.76, Plate 4.6).

Silurian-Devonian Carbonates. This section is exposed at the surface in parts of Adair, Casey, Russell, and Pulaski Counties, and it is mostly shallower than 2,500 ft to the east, except for the extreme eastern part of the section on the Pine Mountain Overthrust Block (Fig. 4.76, Plate 4.6). In the Middlesboro Syncline on the Pine Mountain Thrust Block, much of the upper part of this interval (drillers' Corniferous) is missing beneath the sub-Devonian shale unconformity.

Devonian Shale. The Ohio (Chattanooga) Shale is at the surface in parts of Adair, Casey, Russell, and Pulaski Counties, and dips east to depths of more than 1,000 ft east of Laurel County. The shale thickens to the east with depth (Fig. 4.76, Plate 4.6). In front of Pine Mountain, in Knott and northern Bell Counties, the shale is 160 to 200 ft thick and 1,000 to 1,400 ft below sea level (Fulton, 1979). The shale is overthickened on Pine Mountain where the Pine Mountain Thrust Fault occurs within the shale. The shale is exposed at the surface at the base of Pine Mountain. Overthickened and highly fractured shale was encountered in the United Fuel Gas Co. No. 8801A Knuckles well, where the well intersected the thrust fault at depth. The shale in this section is west of its main producing area in the Big Sandy Field of Pike and surrounding counties. Where gas is produced, there is the theoretical possibility of enhanced gas recovery using CO_2, although more research is needed to prove the concept (Nuttall, 2006).

The Ohio (Chattanooga) Shale is deeper than 2,500 ft only on the Pine Mountain Thrust Sheet, so could only be used as a confining interval that would keep any CO_2 injected into underlying units in a supercritical state in that area. On the thrust block, there may be issues of fracturing and faulting that would interfere with the unit's sealing capacity.

Shallower Porosity Horizons Deeper than 2,500 ft. The Mississippian units are mostly shallower than 2,500 ft beneath the Cumberland River (Fig. 4.76, Plate 4.6). They are exposed at the surface on Pine Mountain. Because of topographic relief in eastern Kentucky, however, in front (northwest) of Pine Mountain, parts of the Mississippian may be more than 2,500 ft beneath the surface. Gas was produced from the Upper Mississippian Pennington Formation Maxon sands at depths of 2,584 to 2,596 ft in the Nami Resources Co. LLC No. 21 Lewis Heirs well, Bell County. In this area, the Big Lime (drillers' terminology for the Newman Limestone Formation), which locally is a target for oil and gas exploration, would also be more than 2,500 ft deep.

Coals Deeper than 1,000 ft. The Pennsylvanian coal-bearing strata are less than 1,000 ft beneath the Cumberland River along this section (Fig. 4.76, Plate 4.6). Because of topographic relief in eastern Kentucky, however, in front (northwest) of Pine Mountain, the lower parts of the Pennsylvanian may be more than 1,000 ft below the surface. Density logs were not available at shallow depths for the Nami Resources Co. LLC No. 21 Lewis Heirs well, in Bell County, but the top of the thick quartz sandstones (drillers' Salt sands) is at 1,350 ft. Several thin coal beds may occur in the overlying 350 ft, which would be in the Grundy Formation of Chesnut (1992). In some other states, coal beds in known coalbed-methane fields are being considered for enhanced coalbed methane recovery with CO_2 where there is significant cumulative coal thickness more than 1,000 ft deep. Coalbed methane has not been produced from the coals along this section, and to date, they have not been targets for methane development.

Cumberland River Summary. The Mount Simon, basal, St. Peter, and Rose Run sandstones are absent or have little storage potential along the Cumberland River. The Knox is likely the only possibility for even moderate-scale injection along much of this section. The lower Knox (Copper Ridge) is mostly deeper than 2,500 ft beneath the river. The upper Knox (Beekmantown) is shallower than 2,500 ft in the eastern part of the cross section, but is below 2,500 ft to the west. Salt water is reported from several zones in the Knox. Log profiles show numerous thin, likely fracture-related porosity zones. In one well, circulation was lost in an upper Knox porosity zone. Most of the Knox porosity that can be identified in downhole logs is confined to narrow zones, and more work would be needed to determine the lateral extent of these zones. Use of the Knox for large-scale storage would likely require stacking of multiple porosity zones or openhole completions within the Knox in order to achieve a thick enough zone of sufficient porosity and permeability for injection.

In the easternmost part of the section, there are more units that might have local potential for at least small-scale carbon storage below 2,500 ft depth than to the west. Local reservoirs in the Silurian Tuscarora Sandstone (Clinton sand of drillers' terminology), Lockport Dolomite, Corniferous carbonates, Mississippian Newman Limestone (drillers' Big Lime), and sandstones in the Pennington Formation (drillers' Maxon sands) are possible storage options. More work would be needed to analyze the extent of these porosity zones. Also, the Corniferous and Mississippian reservoirs are common targets for oil and gas exploration and locally may have many well penetrations that would have to be considered as potential pathways for leakage in any injection project.

Other possibilities for carbon storage include the Devonian shale at depths of more than 1,000 ft in the eastern part of the section, and possibly coal beds at depths of more than 1,000 ft immediately west of Pine Mountain. These types of organic reservoirs have yet to be thoroughly tested, and many questions remain about their actual potential for large-scale injectivity. Rather than in large-scale sequestration, smaller amounts of CO_2 might be used for enhanced gas recovery in known methane-producing shales and possibly coal beds, but more research is needed.

Kentucky River

The Kentucky River cross section extends from Owen County south to Garrard County, east to Wolfe County, and then south to Leslie County, approximately along the path of the Kentucky River (Figs. 4.63, 4.77). Frankfort, the state capital, is the largest town along the river. Two branches of the river join at Beattyville. All of the existing power plants are downstream from Beattyville (Table 4.23). Headward (east of Beattyville), the cross section is largely oriented between the two branches of the river. The northern branch extends through Perry and Letcher Counties and includes the town of Hazard. The southern branch extends through Clay and Leslie Counties.

The Kentucky River section was constructed from data from 19 wells (Figs. 4.77–4.78, Plate 4.7, Table 4.24). Eight of the wells reached basement, and all of them at least reached the top of the Knox. Drillers' descriptions of cuttings are available online for the Melcher-Atkins Oil Co. No. 2 Chambers and United Fuel No. 8613T Williams wells. Sample descriptions are available for parts of the Texaco No. 1 Williams well (to 1,520 ft, through part of the Beekmantown Formation), the B-J Inc. No. 1 Duff well (1,290 to 5,840 ft, through part of the Rose Run Sandstone), and Texaco No. 1 Sherrer well (descriptions of sandstones below 4,830 ft.). Twelve boxes of core are in the KGS Well Sample and Core Library for part of the Exxon Corp. No. 1 Banks well. Cores were also drilled for at least part of the Tennessee Corp. O'Donovan, Texaco No. 1 Perkins, and Texaco No. 1 Wolfinbarger wells, but the locations of these cores and whether or not reports were generated for them are uncertain at this time.

Structure and Faults. The Kentucky River cross section cuts across the Cincinnati Arch and Rome Trough. West of Garrard County the river is on the Cincinnati Arch. Between Jessamine and southern Breathitt Counties, the river cuts through rocks above the Rome Trough. The river is oriented along the Lexington Fault System and Grenville Front in Garrard and Jessamine Counties (Fig. 4.77, Plate 4.7). Eastward, the river is just south of the Kentucky River Fault System and crosses the Irvine–Paint Creek Fault System. In southern Breathitt County, the river crosses the southern boundary of the Rome Trough. Fewer wells are near the river on the Cincinnati Arch than to the east in the Rome Trough. Within the Rome Trough, the river (and section) cuts across a series of basement faults. The Kentucky River and Irvine–Paint Creek Fault Systems have surface expression, but many of the other known basement faults do not (Figs. 4.77–4.78). The faults without surface expression are known from seismic analysis. They appear to influence pre-St. Peter strata significantly more than they do post-St. Peter strata.

Precambrian Basement. The East Continent Rift Basin has been interpreted from seismic data beneath the Kentucky River, west of the Grenville Front (Drahovzal, 1997). West of the Grenville Front, the top of the Precambrian is approximately 3,000 ft below sea level. Crystalline basement is much deeper, however, because of a thick section of Precambrian Middle Run sedimentary strata in the rift basin (Fig. 4.78, Plate 4.7). True crystalline basement in this area is estimated to be more than 25,000 ft deep. Northward, several faults cut the Middle Run, and basement varies from 17,500 to 22,500 ft below sea level. East of the Grenville Front, strata beneath the Kentucky River thicken into the Rome Trough and crystalline basement varies from 5,000 to more than 10,000 ft below sea level. South of the southern boundary fault of the Rome Trough, basement rises from more than 12,000 ft below sea level in the trough to approximately 8,000 ft below sea level outside of the fault (see "Rock Unit Summary").

Middle Run Formation. The Middle Run Formation occurs beneath the Kentucky River east of the Lexington Fault System (and Grenville Front). Basalts (515 ft thick) in the Middle Run Formation were penetrated in the Texaco No. 1 Sherrer well from 3,280 to 3,795 ft ("b" in Figure 4.78). Bedding thicknesses may be overestimated because bedding in cores from lower in the well was at a very high angle. Sample descriptions indicate that basalts have been thoroughly altered by hydrothermal solutions (although overlying sedimentary rocks were not). Beneath the basalts, Precambrian sandstones were penetrated in intervals from 4,830 to 5,010 ft, 5,150 to 5,190 ft, and 5,190 to 5,800 ft. Sandstones were reported as feldspathic with calcite cements. Sandstones in the lower part of the well were described as so well-cemented that they were like quartzite (a hard, quartzose metamorphic rock).

The extent and thickness of the formation has been interpreted from seismic data (see "Rock Unit Summary"). Along the river, the Middle Run is estimated to be approximately 17,500 ft thick to the north and more than 20,000 ft thick adjacent to the Grenville Front (Drahovzal and others, 1992).

Mount Simon Sandstone. The Mount Simon should underlie the Kentucky River west of the Lexington Fault System in Garrard County. No wells penetrate the Mount Simon in the western part of the section, so interpretations of thickness are based on regional correlations (see "Rock Unit Summary"). The sandstone thins from north to south, from approximately 400 ft at the mouth of the river in Carroll County to zero in the Texaco No. 1 Sherrer well in Jessamine County (Fig. 4.78, Plate 4.7). It should occur at depths of 3,500 to 4,000 ft. Little is known about the porosity of the sandstone in the area of the Kentucky River, but it is one of the only possible reservoirs for carbon storage on the Cincinnati Arch east of the Lexington Fault System. Tests of the sandstone in the Midwest Regional Carbon Sequestration Partnership test at Duke Energy's East Bend Power Station in Boone County will provide data on the unit's carbon storage potential in central Kentucky. Research is needed to determine if porosity intervals in the Mount Simon extend westward to the Kentucky River, and how far south they extend in central Kentucky.

Basal Sandstone. The basal sandstone occurs above Precambrian basement rocks in the Rome Trough east of the Lexington Fault System. The interval is penetrated in seven of the wells in the Kentucky River section (Fig. 4.78, Plate 4.7, Table 4.24). The basal sandstone is

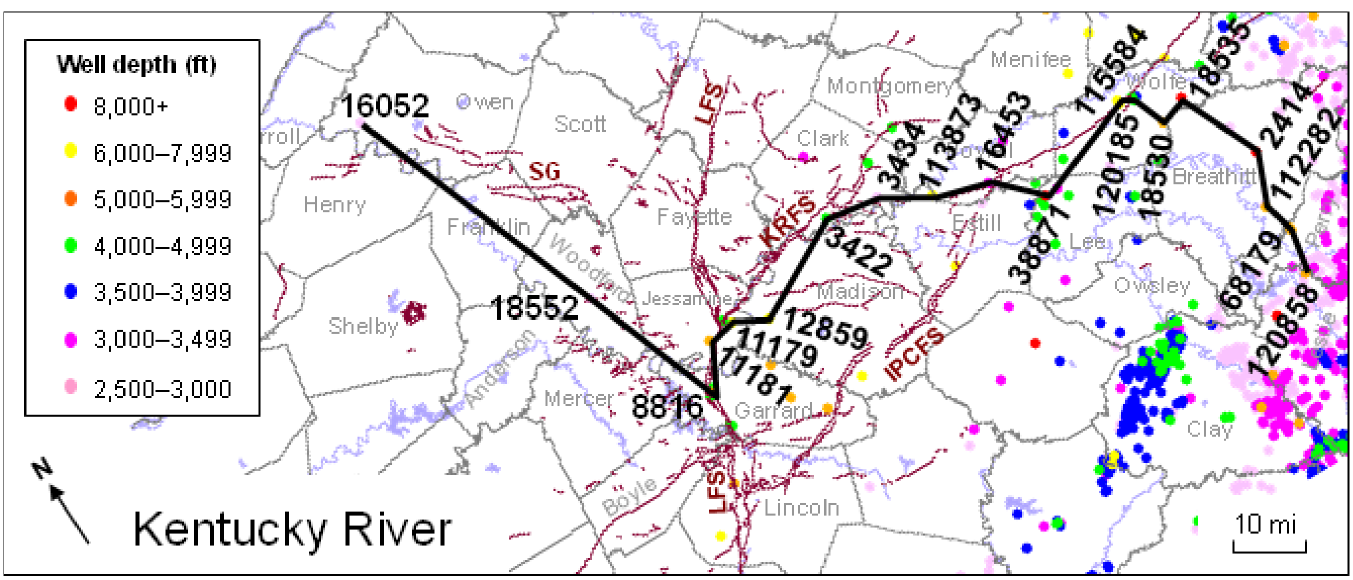

Figure 4.77. Location of the Kentucky River cross section. Wells used in the section are labeled by their record number (see Table 4.24). Locations of other wells in the vicinity are color-coded for depth. Wells less than 2,500 ft in depth are not shown. Faults exposed at the surface are shown as brown lines. The map is oriented to better fit the page. IPCF = Irvine–Paint Creek Fault System. KRF = Kentucky River Fault System. LF = Lexington Fault System. SG = Sweitzer Graben.

Table 4.23. Electric-power-generating stations along the Kentucky River in Kentucky. Data from Kentucky Public Service Commission (June 10, 2008) and Energy Information Administration (2006).

Owner	*Plant Name*	*Capacity (MW)*	*Fuel*	*County*
Kentucky Utilities	Tyrone	75	coal	Woodford
Kentucky Utilities	Tyrone	62	fuel oil	Woodford
Kentucky Utilities	E.W. Brown	981	coal	Mercer
Kentucky Utilities	E.W. Brown	739	gas, fuel oil	Mercer
Eastern Kentucky Power	Dale	216	coal	Clark
Eastern Kentucky Power	J.K. Smith	859	natural gas	Clark

4,766 ft deep in the Texaco No. 1 Williams well (Clark County) and more than 12,159 ft deep in the Exxon No. 1 Banks well (Wolfe County). The interval is generally around 300 ft thick on the western end of the trough, but has variable thickness elsewhere and is as thin as 27 ft in the Texaco Williams well. Also, in many wells the basal sandstone interval is dominated by shales and siltstones rather than sandstones. Lateral variation in sandstones between the Texaco No. 1 Wolfinbarger (Jessamine County) and Texaco No. 1 Perkins (Madison County) wells is shown in Figure 4.16. In the deeper wells (more than 7,000 ft), the basal sands do not exhibit porosity, but shallower occurrences have had minor indications of porosity along the river. The Texaco No. 1 Kirby well (Garrard County), which is near the river but south of the line of the cross section, had a show of oil in the basal sands at 4,612 ft. Similarly, a show of gas was reported in basal sands in the Kin-Ark Oil Hager well at 4,360 ft, just off the line of the section in Jessamine County. In both of the Wolfe County wells, salt water was encountered in the basal sands. In the Miller Oil No. 1 Chichester well, salt water was reported from 6,890 to 6,930 ft, and an oil and condensate show was reported at 6,880 ft. In the nearby Miller No. 1 Bailey well, the basal sand had a good gas show at 6,960 ft, and salt water was reported from 6,953 to 6,960 ft. This well was treated with acid and 60 tons of CO_2. Following treatment it produced minor gas, 1,000 barrels of water, and was plugged and abandoned. Further information is not available. There may be a correlative porosity horizon between the two wells in the basal sand. The use of CO_2 during treatment of the well shows that at least small amounts of CO_2 can be safely injected into this subsurface reservoir.

Rome Formation. The Rome is penetrated in seven wells along this section (Fig. 4.78, Plate 4.7). It underlies the river east of the Lexington Fault System in the Rome Trough. Thick sandstones in the Rome are concentrated along the Lexington and Kentucky River Fault Systems. The sandstones are 500 to 700 ft thick along the faults and thin rapidly to the south and east (see "Rock Unit Summary"). The Kentucky River is south of much of the known thick Rome sandstones east of Clark County. Lateral variation of the sandstones between the Texaco No. 1 Wolfinbarger (Jessamine County) and Texaco No. 1 Perkins (Madison County) wells is shown in Figure 4.15. Gas and water were reported at 4,540 ft in the Texaco No. 1 Wolfinbarger well. In the Texaco No. 1 Perkins well (Madison County), a drillstem test from 4,736 to 4,756 ft recovered 780 ft of gas-cut water and 420 ft of mud-cut water. A drillstem test was also attempted in the Cumberland-Harlan No. 1 Shumate Heirs well (Powell County) at 5,490 to 5,565 ft, but a packer failed. A gas show was reported in the Rome at 6,266 ft in the Miller Oil No. 1 Bailey well (Wolfe County). Salt water was encountered in the Rome from 6,300 to 6,360 ft in the Miller Oil Co. No. 1 Chichester well (Wolfe County). Just off the line of the section, the South-Central Hall well in Powell County had a show of oil and gas in the Rome at 5,913 ft; the Lancaster Exploration Lee well had a show of gas in the Rome at 4,536 ft.

Structural traps are the primary target for pre-Knox gas exploration in the Rome Trough and are discussed in Harris and Baranoski (1996). Sandstones and fractured shales along the fault-bound margin of the trough have been responsible for most of the production to date; however, all known production is from single-well fields, so the lateral extent of the porosity intervals has not been evaluated. Thicknesses of pay zones in the Rome vary from 10 to 100 ft, and average 41 ft. Rock pressure ranges from 2,708 to 11,710 psi and averages 6,139 psi. Completion practices range from acid fracturing of openhole intervals to conventional acid treatment through perforated casing (Harris and Baranoski, 1996).

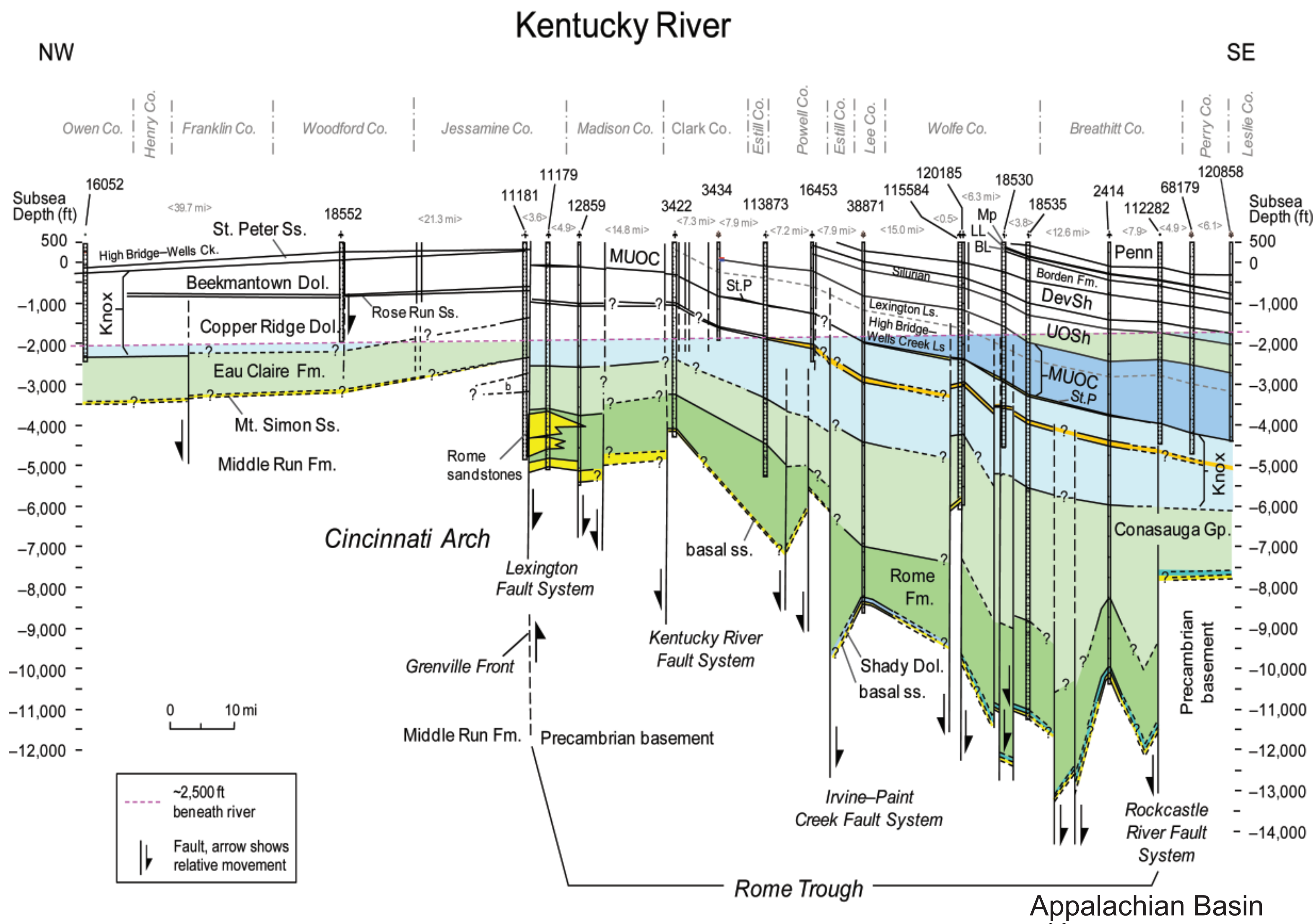

Figure 4.78. Kentucky River cross section showing intervals discussed in the "Rock Unit Summary." Intervals are color-coded according to their generalized carbon-storage category, as shown in Figure 4.5. Location of section shown in Figure 4.77. Wells used in this section are listed in Table 4.24. Expanded cross section with geophysical logs is shown in Plate 4.7. Faults visible at the surface are solid at the top and dashed downward. Faults that can be mapped at the surface are shown as solid at the top and dashed downward on the cross section. Faults that are not visible on the surface, but have been detected at depth from seismic analysis, are shown as solid at the bottom and dashed upward in the cross section. Surface faults connect to basement faults, but the level at which they connect or split is uncertain without specific data at that location. b=basalts in the Middle Run Formation, Con.=Conasauga Group, DevSh=Devonian shale, MUOC=Middle–Upper Ordovician carbonate interval. Penn.=Pennsylvanian strata. SDC=Silurian–Devonian carbonate interval, StP=St. Peter Sandstone, and UOSh=Upper Ordovician shale.

Table 4.24. Information on wells used for the Kentucky River cross section. Record numbers can be used to view well data in the KGS Oil and Gas Database.

Permit No.	*Record No.*	*Well Name*	*County*	*Elevation (ft)*	*Total Depth (ft)*	*Formation at Total Depth*	*Samples*
18849	16052	Tennessee Corp. BT3 O'Donovan	Owen	467	2,900	Eau Claire Formation (Cambrian)	core?
21801	18552	Phillip Agrois 1 Gaines	Woodford	852	2,812	Copper Ridge Dolomite (Cambrian)	X
18114	11181	Texaco 1 Sherrer	Jessamine	947	5,800	Middle Run Formation (Precambrian)	X
20747	11179	Texaco 1 Wolfinbarger	Jessamine	966	6,072	Precambrian basement	X
21905	12859	Texaco 1 Perkins	Madison	940	6,415	Precambrian basement	
22398	3422	Texaco 1 Williams	Clark	650	4,937	Precambrian basement	X
17516	3434	Melcher-Atkins Oil 2 Chambers	Clark	837	2,775	Copper Ridge Dolomite (Cambrian)	X
39272	113873	Cumberland Harlan 1 Shumate	Powell	747	6,040	Rome Formation (Cambrian)	X
17445	16453	Petroleum Exploration 1 Tipton	Powell	869	3,304	Copper Ridge Dolomite (Cambrian)	X
60010	38871	Ashland 1 Cable	Lee	1,005	9,644	Precambrian basement	X
89379	115584	Miller Oil & Gas 1 Bailey	Wolfe	1,038	7,106	Precambrian basement	
90214	120185	Miller Oil & Gas 1 Chichester	Wolfe	989	6,968	Rome Formation (Cambrian)	
17590	18530	Holly Creek 2 White	Wolfe	943	5,500	Copper Ridge Dolomite (Cambrian)	
30520	18535	Exxon Corp. 1 Banks	Wolfe	1,028	12,288	Precambrian basement	core
611E8	2414	United Fuel 8613T Williams	Breathitt	750	11,130	Precambrian basement	
87061	112282	Alamco Inc. 6068 EREX	Breathitt	862	5,336	Knox Group (Ordovician)	X
53723	68179	B-J Inc. 1 Duff	Perry	1,137	5,860	Rose Run Sandstone (Cambrian)	X
90858	120858	John Henry Oil Huff 3 Hignite	Leslie	1,210	5,622	Knox Group (Ordovician)	

Eau Claire–Conasauga Group. The Eau Claire Formation becomes the Conasauga Group east of the Lexington Fault System in the Rome Trough (Fig. 4.78, Plate 4.7). The top of the Eau Claire is reached only in one well on the western end of the section and its thickness is estimated from regional trends. The Eau Claire shallows to less than 2,500 ft deep on the Jessamine Dome (crest of the Cincinnati Arch). Westward the Eau Claire is equivalent to the Conasauga Group. The Conasauga is penetrated in nine wells along this section (Fig. 4.78, Plate 4.7). It deepens from 4,300 ft on the western end of the Rome Trough to 7,596 ft in the Exxon No. 1 Banks well (Wolfe County). Sandstones in this interval seem to be concentrated near the Lexington and Kentucky River Fault Systems along this section. The Texaco No. 1 Wolfinbarger well encountered gas and water at 4,350 ft in a sandstone in the Maryville Limestone, in the upper Conasauga Group. Four cores were taken from 4,354 to 4,384 ft (30 ft thick), and are described as consisting of medium white sandstone. A drillstem test in the same interval from 4,518 to 4,550 ft in the Texaco No. 1 Perkins well recovered 190 ft of salt water and 200 ft of mud. In the Texaco No. 1 Kirby well (south of the section in Garrard County), gas and water were reported at 4,550 ft, which is 8 ft from the top of the Maryville Limestone. These intervals are generally thin, and their lateral extent is uncertain.

The Nolichucky Shale occurs in the upper part of the Conasauga Group. It is 650 to 1,200 ft thick. Where these shales are unfaulted, they would likely provide an adequate seal to CO_2 injection in underlying Maryville or deeper sandstones, if any are encountered.

Lower Knox–Copper Ridge Dolomite. The Copper Ridge is penetrated in 17 wells along this section (Fig. 4.78, Plate 4.7). The top of the Copper Ridge is shallower than 2,500 ft west of the Cumberland-Harlan No. 1 Shumate well in Powell County. It deepens to more than 5,860 ft in the B-J Inc. No. 1 Duff well in Perry County. Water was reported in the Copper Ridge at 2,741 ft (110 ft from the base) in the Petroleum Exploration No. 1 Tipton well (Powell County). Salt water and an oil and gas show were reported from 5,171 to 5,180 ft in the Copper Ridge (1,013 to 1,022 ft from the top) in the Miller Oil No. 1 Bailey well. In the nearby Miller Oil No. 1 Chichester well, the Copper Ridge had gas shows at 4,280 ft (278 ft from the top) and 5,052 ft (1,050 ft from the top). There were also gas shows from 5,110 to 5,126 ft (1,108 to 1,124 ft from the top). The deeper interval may represent a correlative zone between the two wells.

Gas and 4,000 ft of black sulfur water were reported in the Holly Creek No. 2 White well (Wolfe County) at a depth of 4,893 to 4,905 ft in the upper Copper Ridge. This zone is 16 ft beneath the Rose Run Sandstone, and perhaps some of this water was associated with the Rose Run rather than the upper Copper Ridge. Gas and salt water were also reported at 5,067 to 5,080 ft.

Rose Run Sandstone. The Rose Run is penetrated in most of the wells along this section (Fig. 4.78, Plate 4.7). The Rose Run is shallower than 2,500 ft west of the Cumberland-Harlan No. 1 Shumate well in Powell County. It deepens to more than 5,825 ft in the B-J Inc. No. 1 Duff well in Perry County. Several wells on the Kentucky River section reported porosity in the Rose Run. In the Cumberland-Harlan well, sulfur water was noted from 2,592 to 2,657 ft. An attempt to perforate and complete the well from 2,594 to 2,599 ft and 2,650 to 2,656 ft filled up with 400 ft of water after perforation. Salt water with gas shows was reported in the Miller Oil No. 1 Bailey well from 3,998 to 4,014 ft (16 ft thick) and from 3,960 to 3,990 ft (30 ft thick) in the nearby Miller No. 1 Chichester well. This may represent a correlative porosity zone in the Rose Run. A drillstem test was performed in the United Fuel 8613T Williams well in the Rose Run from 5,140 ft (near the base of the Beekmantown) to 5,250 ft and recovered 115 ft of salt water. Perforations from 5,190 to 5,232 ft resulted in a show of gas and oil and salt water. Porosity was also noted in the Rose Run in the Ashland Exploration No. 1 Cable well from 3,870 to 3,932 ft, but with no water or oil or gas shows.

At depths of less than 2,500 ft, porosity was noted in the Melcher-Atkins well in the Trapp Oil Field, Clark County. From 2,410 to 2,416 ft, the sandstone averaged 22 percent porosity, with 20 percent water saturation. From 2,470 to 2,478 ft, the sandstone varied from 22 to 24 percent porosity, with 18 to 21 percent water saturation.

Upper Knox–Beekmantown Dolomite. The upper Knox is penetrated in all of the wells along this section (Fig. 4.78, Plate 4.7). The top of the Knox is less than 2,500 ft deep west of the Ashland Exploration No. 1 Cable well in Lee County. East of Lee County are several shows of water, oil, or gas in the upper Knox. There was a show of gas in the Ashland Cable well from 3,206 to 3,351 ft (217 to 362 ft from the top of the Knox). In the Miller Oil No. 1 Bailey well (Wolfe County), gas shows were reported at 3,494 ft (88 ft from the top of the Knox) and 3,740 ft (334 ft from the top of the Knox), salt water and a show of oil and gas were reported from 3,871 to 3,877 ft (465 ft from the top of the Knox), and a gas show was reported at 3,888 ft (482 ft from the top of the Knox). Scattered gas shows were also reported from the Beekmantown in the nearby Miller Oil No. 1 Chichester well. Salt water was reported in the Chichester well from 3,540 to 3,600 ft (178 to 238 ft from the top of the Knox). In the Holly Creek No. 2 White well, a perforated zone from 3,916 to 3,921 ft and 3,925 to 3,930 ft in the St. Peter and top of the Knox recovered gas and oil (more details were listed for the St. Peter Sandstone). The B-J Inc. No. 1 Duff well is a shut-in gas well, which had gas in the upper Knox from 5,390 to 5,400 ft (290 to 300 ft from the top of the Knox) in fractured dolomite.

West of Lee County, the Petroleum Exploration 1 Tipton well (Powell County) encountered minor gas and water at 2,190 ft in an 8 to 10 percent porosity zone 28 ft from the top of the Knox, and water in an 8- to 10-ft zone at 2,741 ft (580 ft from the top of the Knox).

St. Peter Sandstone. The St. Peter interval is penetrated in all of the wells along this section (Fig. 4.78, Plate 4.7), but sandstone is absent in some wells. The sandstone produces from two major fields in the Kentucky River area: the Trapp Field in Clark County and the Irvine-Furnace Consolidated Field on the Estill-Powell County border. Two minor fields have also had production further upstream: the Holly Creek Consolidated Field in eastern Wolfe County and the Canyon Falls Field in Lee County. The Trapp Field is on the downdropped side of the Kentucky River Fault System and the Irvine-Furnace Consolidated Field is on the downdropped side of the Irvine–Paint Creek Fault System. Data from the fields are given in Table 4.25 and are summarized in Humphreys and Watson (1996). Price (1981) reported cumulative production of 1.8 bcf from the Irvine-Furnace Consolidated Field.

Traps in the few St. Peter fields known in eastern Kentucky are all related to structure, including faulted anticlines, unfaulted anticlines, and possibly fault traps (Humphreys and Watson, 1996). Most fields are underpressurized. Both the Trapp and Irvine-Furnace Consolidated Fields had high concentrations of natural carbon dioxide and nitrogen, which lowered the Btu value of the gas. High CO_2 (43 percent) was also noted in the Holly Creek No. 2 White well. These fields show that the sandstones can safely store CO_2.

The top of the St. Peter is less than 2,500 ft deep west of the Ashland Exploration No. 1 Cable well in Lee County. In the western part of the section, the thickness of the sandstone is variable, and several wells have no St. Peter. The Ashland Cable well has 10 to 12 ft of porous sandstone at a depth of 2,966 ft. The Holly Creek No. 2 White well (Breathitt County) perforated a zone from 3,916 to 3,921 ft and 3,925 to 3,930 ft in the St. Peter and top of the Knox, and recovered gas and oil (the high CO_2-content gas noted above). The Exxon No. 1 Banks well (Wolfe County) had a small gas flare at 4,300 to 4,374 ft in the St. Peter.

Middle-Upper Ordovician Carbonates. This interval is at the surface along the Kentucky River in parts of Jessamine and surrounding counties, and is penetrated in all of the wells along this section (Fig. 4.78, Plate 4.7). The top of the interval is deeper than 2,500 ft east of Wolfe County. There was a gas show in the Miller Oil No. 1 Chichester well from 3,282 to 3,288 ft in the lower High Bridge or Wells Creek Dolomite. Gas was also checked for in the Tyrone Formation at 3,714 to 3,740 ft and Wells Creek Dolomite at 4,629 ft. Fractured carbonates without water, gas, or oil shows were noted in the John Henry Oil well from 4,905 to 5,008 ft in the High Bridge Group. For the most part, this interval is tight, and only minor, narrow porosity intervals are known along the Kentucky River below 2,500 ft. Fractured carbonate reservoirs have been found along the southern boundary fault of the Rome Trough west of the section and are summarized in the "Rock Unit Summary."

Upper Ordovician Shale. The Upper Ordovician shale interval consists of interbedded limestone and shale, and becomes shalier to the southeast. This interval is at the surface in central Kentucky and is more than 2,500 ft deep only in the easternmost part of the section. Where the unit is more than 2,500 ft deep, contained thick shale, and was unfaulted, it could provide adequate sealing properties to injection of CO_2 in any deeper reservoirs.

Tuscarora (Clinton) Sandstone. Silurian strata are at the surface in Clark, Estill, and Powell Counties along the river, and are absent west of those counties (Fig. 4.78, Plate 4.7). Sandstones in the Clinton (Rose Hill) Formation pinch out in the subsurface before reaching the surface. The Clinton is more than 2,500 ft deep east of the Alamco-EREX well (Breathitt County) and does not contain porous sandstones along this part of the river.

Silurian Shale. The Silurian Rose Hill (Clinton) Shale is more than 200 ft thick but more than 2,500 ft deep only on the eastern end of the section (Fig. 4.76, Plate 4.6). The shale should have good confining characteristics where it is thick and more than 2,500 ft deep.

Table 4.25. Some reservoir characteristics for the St. Peter Sandstone in fields of the Kentucky River area. Data from Humphreys and Watson (1996).

Field	*Depth (ft)*	*Area (acres)*	*Pay Thickness*		*Log Porosity (%)*		*Core Porosity (%)*	*Permeability (md)*
			(log ft)	(mean)	(range)	(mean)		
Irvine-Furnace	2,527	880	20	10	8–12	8	4–12	14
Trapp	1,598	1,000	23	13	7–19	12	7–19	14.1

Keefer (Big Six) Sandstone. Silurian strata are at the surface in Clark, Estill, and Powell Counties along the river, and are absent west of those counties (Fig. 4.78, Plate 4.7). The drillers' Big Six pinches out or laterally interfingers with carbonates in the subsurface before reaching the surface.The sandstone is more than 2,500 ft deep only on the easternmost end of the section, and no porosity is noted in wells in that part of the section.

Silurian-Devonian Carbonates. Silurian and Devonian strata are at the surface in Clark, Estill, and Powell Counties along the river, and are absent west of those counties. The drillers' Corniferous is the primary production zone in the Big Sinking and Irvine-Furnace Fields (as well as in many smaller fields) along the river, but at much shallower depths than are needed for large-scale, miscible carbon storage. The top of the drillers' Corniferous is only deeper than 2,500 ft on the westernmost end of the section (Fig. 4.78, Plate 4.7). The B-J No. 1 Duff well (2,660 to 2,700 ft) and John Henry Hignite Heirs well (2,778 to 2,882 ft) are both shut-in gas wells in the Corniferous.

Devonian Shale. The Ohio Shale crops out at the surface in Estill and Powell Counties along the river, and is absent west of those counties. It is more than 1,000 ft deep east of Wolfe County, and dips east to 2,778 ft in the John Henry Huff well in Leslie County (Fig. 4.78, Plate 4.7). Between Wolfe and Leslie Counties the shale is 200 to 300 ft thick along the section (Fulton, 1979). The Devonian shale in this section is west of its main producing area in the Big Sandy Field of Pike and surrounding counties. Where gas is produced, there is the theoretical possibility of enhanced gas recovery using CO_2, although more research is needed to prove the concept (Nuttall, 2006).

The Ohio Shale is deeper than 2,500 ft only on the easternmost end of the cross section, so could only be used as a confining interval that would keep any CO_2 injected into underlying units in a supercritical state in that area.

Shallower Porosity Horizons Deeper than 2,500 ft. Shallower porosity horizons have not been identified along this section, but south of the area in Leslie and Perry Counties, the Mississippian Newman Limestone (drillers' Big Lime) may have some sequestration potential. Anderson and others (2008) investigated several deep Big Lime oil fields for enhanced oil recovery potential with CO_2. Pore volumes for potential sequestration were calculated for the Bull Creek, Cutshin, Daley, and Bulan Fields. These fields are also discussed in chapter 2.

Coals Deeper than 1,000 ft. Thin, laterally restricted Lower Pennsylvanian coal beds are possibly deeper than 1,000 ft on the westernmost end of the section where the drillers' salt sands are more than 1,000 ft deep (Fig. 4.78, Plate 4.7). In other states, coal beds in known coalbed-methane fields are being considered for enhanced coalbed methane recovery with CO_2, where there is significant cumulative coal thickness more than 1,000 ft deep. Coalbed methane has not been produced from these beds, and to date they have not been targets for methane development. Significant cumulative coal thickness (20 to 30 ft) more than 1,000 ft deep (below drainage depth) is unlikely.

Kentucky River Summary. On the Cincinnati Arch (west of the Lexington Fault System) the only potential reservoirs for carbon storage are in the Mount Simon Sandstone. No wells are along this section in the Mount Simon, so its porosity and permeability are unknown along the river at this time. Based on regional analysis, however, the best chance for intersecting thicker sandstones is closer to the mouth of the Kentucky River at the Ohio River. South (and east) along the river, the sandstone thins and may not have potential for carbon storage.

East of the Lexington Fault System (eastern Garrard, Madison, and southern Clark Counties), the best potential for thick, porous reservoirs is in the Rome Formation. Rome sandstones commonly exhibit several hundred feet of good porosity at depths of 4,500 to 6,500 ft along the Lexington and Kentucky River Fault Systems, but thin rapidly away from the faults. These sands have the thickest cumulative porosity in Kentucky. Their proximity to faults, however, means that the faults would likely have to be tested near any potential storage site to demonstrate they were not pathways for potential leakage. Also, fault density in the area where the sandstone is known to be thick means a large-scale injection project would have faults in its area of influence.

Aside from the Rome sands along the margin of the Rome Trough, several other stratigraphic horizons have exhibited smaller-scale porosity along the Kentucky River. There may be areas where multiple reservoirs could be stacked to create space for large-volume carbon storage. The basal sands have had porosity and water at depths of 4,300 to 7,000 ft in several wells along the river. In one well, CO_2 has already been used for treatment, which shows that at least small amounts can be injected into that reservoir. The extent and potential storage volume of the basal sands is unknown. Porosity has been reported from numerous wells in the Rose Run Sandstone (2,500 to 5,300 ft depth) and the upper Knox Beekmantown Dolomite (2,500 to 5,500 ft depth) in the central and eastern part of the section. These intervals may offer possibilities for small- to moderate-scale carbon storage, but more work is needed to illustrate that known porosity intervals are interconnected or have some regional extent. The St. Peter also has possibilities and is a known gas reservoir (including natural CO_2) along the river. St. Peter thickness and porosity are variable, however, and there is significant fault control on thickness; much of the known porosity is at depths of less than 2,500 ft.

South of the area, the Newman Limestone (drillers' Big Lime) may have potential at depths greater than 2,500 ft for sequestration and enhanced oil recovery. Several oil fields were examined in a regional study for TECO Energy (Anderson and others, 2008). There are also several large oil and gas fields at depths of less than 2,500 ft that have had secondary recovery along the Kentucky River. The Irvine-Furnace, Big Sinking Consolidated, and Big Andy Fields are all discussed in chapter 2. They are too shallow and have too many old well penetrations to be considered for large-scale carbon storage, but CO_2 has already been used in small amounts for secondary recovery in the Big Andy Field (near Big Sinking), and there may be possibilities for more use of CO_2 in other fields along the river. The many well penetrations in some of the larger fields will complicate and may preclude extensive use of CO_2 for secondary recovery in some areas.

Tug Fork

The Tug Fork section begins in the Ashland area, Boyd County, and continues south to Pike County (Fig. 4.63). The fossil-fuel power plants along Tug Fork are all near the confluence with the Ohio River in Lawrence County (Table 4.26).

The Tug Fork section is constructed from data from 19 wells (Figs. 4.79–4.80, Table 4.27, Plate 4.8). Only two of the wells reach basement. Southward along the section, basement deepens significantly. Across much of the section, the deepest penetrations are only into the Devonian shale, which is a primary target for natural gas exploration in this area. Drillers' descriptions of cuttings are available online for the United Fuel Gas No. 8610T Jasper well. Ryder and others (1997) published a cross section across the central Appalachian Basin that parallels the Tug Fork for part of its length, and provides a good reference for the subsurface geology of the area.

Structure and Faulting. The Tug Fork section crosses the Rome Trough. Information about the structures along the section can be found in McGuire and Howell (1963), Ammerman and Keller (1979), Webb (1980), Sutton (1981), Drahovzal and Noger (1995), Ryder and others (1997), and Harris and others (2004). The northern edge of the trough is marked by a series of downstepping basement faults in central Boyd County on the northern end of the section (Fig. 4.80, Plate 4.8). These faults do not have surface expression (although Pennsylvanian strata dip into the Allegheny Synclinorium/Parkersburg Syncline), and have been mapped based on seismic analysis. Southward, the trough is broken into a series of fault blocks. The Walbridge Fault is a surface expression of one of these faults. The deepest part of the trough along Tug Fork is in northern Martin County. The southern boundary is a fault in southern Martin County (no surface expression), which is situated just south of the Irvine–Paint Creek Fault System and north of the Pike County Arch of Sutton (1981).

In northern Pike County, the section crosses the D'Invilliers Structure (Fig. 4.80, Plate 4.8). This structure was interpreted as a strike-slip fault by Drahovzal and Noger (1995) and as a normal fault along the margin of the Southern West Virginia Arch of Kulander and Dean (1978, 1986) in the cross section of Ryder and others (1997). Drahovzal and Noger (1995) interpreted relative down-to-the-south offset along this

Table 4.26. Electric-power-generating stations along the Kentucky side of Tug Fork. Data from Kentucky Public Service Commission (June 10, 2008) and Energy Information Administration (2006).

Owner	*Plant Name*	*Capacity (MW)*	*Fuel*	*County*
American Electric Power	Big Sandy	1,097	coal	Lawrence
Dynergy	Riverside	1,150	natural gas	Lawrence
Dynergy	Foothills	460	natural gas	Lawrence

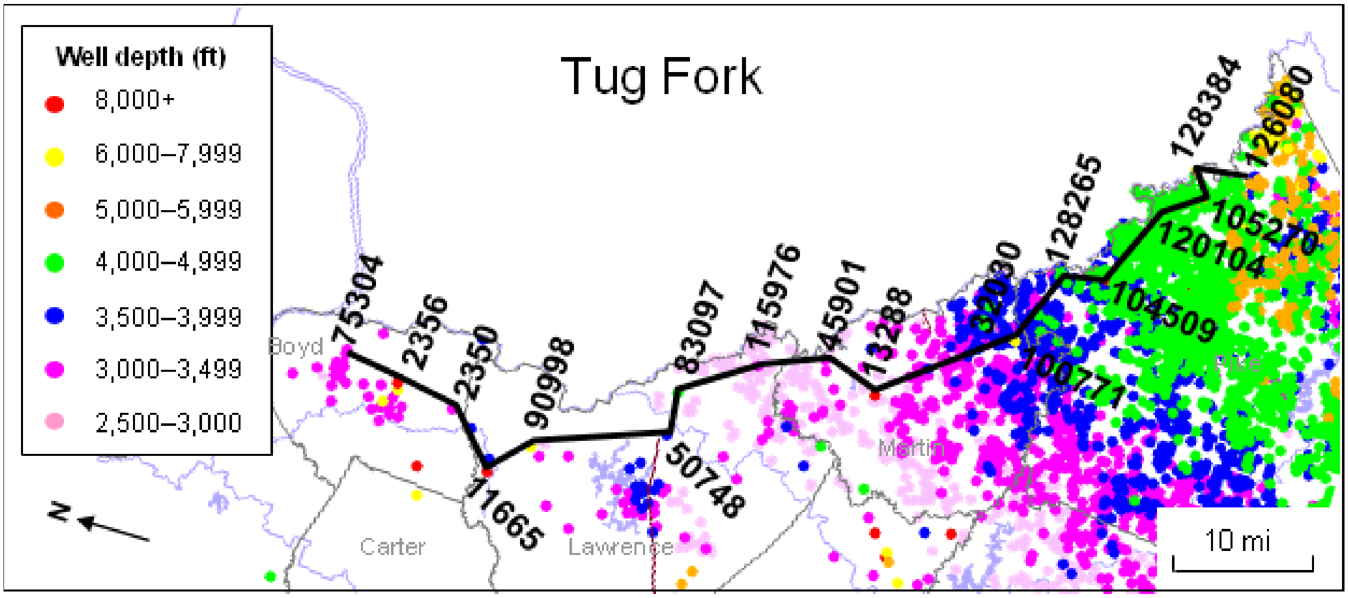

Figure 4.79. Location of the Tug Fork cross section. Wells used in the section are labeled by their record number (see Table 4.27). Locations of other wells in the vicinity are color-coded for depth. Wells less than 2,500 ft in depth are not shown. Faults exposed at the surface are shown as brown lines. The map is oriented to better fit the page.

fault in eastern Kentucky, whereas Ryder and others (1997) interpreted relative down-to-the-north offset east of the river in Mingo County, W.Va. No deep wells are in this part of Pike County, nor any seismic data, so uncertainty remains about this structure. In the Ryder and others (1997) interpretation, this structure is the southern boundary of the Rome Trough in West Virginia, just east of Tug Fork.

Overall, structural dip along the Tug Fork section is controlled by the Rome Trough for strata older than the Cambrian-Ordovician Knox Group and for strata younger than the Knox by the eastward dip into the Appalachian Basin.

Precambrian Basement. Only two wells penetrate basement along Tug Fork, and both are in the northern part of the section (Fig. 4.80, Plate 4.8, Table 4.27). Based on seismic information, Precambrian basement is estimated to range from approximately 6,000 ft to more than 17,000 ft below sea level along the eastern border of Kentucky (Drahovzal and Noger, 1995). The shallowest part of the section is north of the Rome Trough in northern Boyd County. The deepest part of the section is along the southern edge of the Rome Trough, just south of the Irvine–Paint Creek Fault System and Warfield Fault in northern Martin County (Drahovzal and Noger, 1995). Just east of Martin County, Ky., in Mingo County, W.Va., the Columbia Gas Transmission No. 8674-T Mineral Tract 10 well hit basement at 19,591 ft (Ryder and others, 1997). Basement depth varies significantly because of complex structures within and along the borders of the Rome Trough. South of the Rome Trough, in Pike County, basement rises in elevation from between 17,000 and 14,000 ft below sea level to 10,000 ft below sea level on the Pike County Uplift (also called the Pike County Arch).

Mount Simon Sandstone. The northern part of the Tug Fork section may be east of the pinchout of the Mount Simon, or at best, the sandstone would be thin. The sandstone is not recognized within the Rome Trough.

Basal Sandstone. The basal sand was penetrated in the two basement tests on the northern side of the section (Fig. 4.80, Plate 4.8). Sandstones were encountered at depths of 9,315 to 9,385 ft (70 ft thick) in the Inland Gas McKeand well and 12,426 to 12,544 ft (118 ft thick) in the Inland Gas Young well. It likely occurs to the south within the Rome Trough, but it would be at great depths where porosity is unlikely.

Rome Formation. Three wells penetrate the Rome along this section (Fig. 4.80, Plate 4.8). The Inland Gas McKeand well hit a relatively thin section of Rome Formation on the northern lip of the Rome Trough. To the south, the Inland Gas Young well (Lawrence County) intersected a much thicker (and deeper) Rome section in the Rome Trough, and the United Fuel Gas Jasper well (Martin County) reached total depth in the

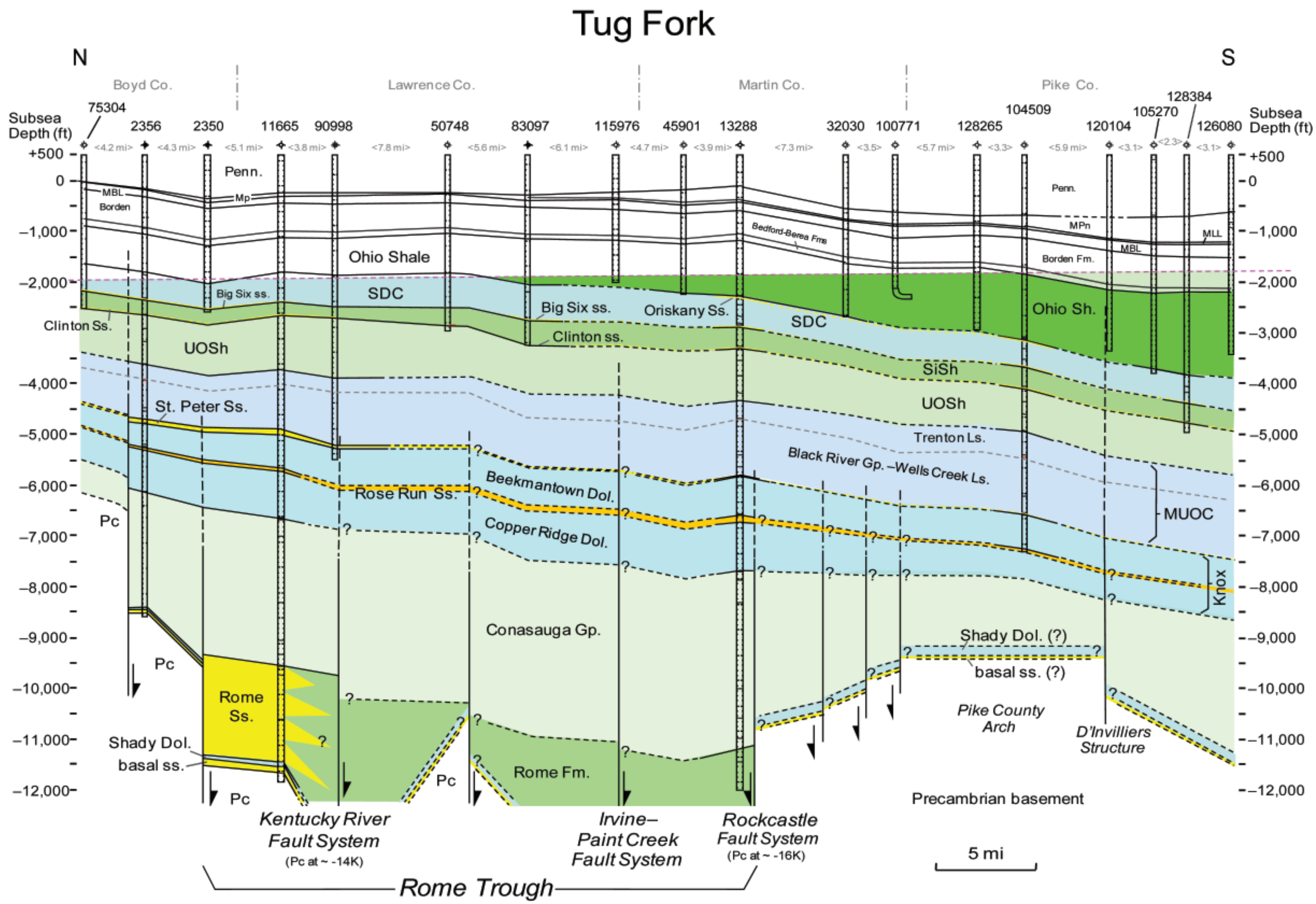

Figure 4.80. Tug Fork cross section showing intervals discussed in the “Rock Unit Summary.” Intervals are color-coded according to their generalized carbon-storage category as shown in Figure 4.5. Location of section is shown in Figure 4.79. Wells used in this section are listed in Table 4.27. Expanded cross section with geophysical logs is shown in Plate 4.8. Faults that can be mapped at the surface are shown as solid at the top and dashed downward on the cross section. Faults that are not visible on the surface, but have been detected at depth from seismic analysis, are shown as solid at the bottom and dashed upward in the cross section. Surface faults connect to basement faults, but the level at which they connect or split is uncertain without specific data at that location. MBL=Mississippian drillers’ Big Lime, MLL=Mississippian drillers’ Little Lime, Mp=Mississippian Pennington Formation, MUOC=Middle–Upper Ordovician carbonate interval, PC=Precambrian basement SDC=Silurian–Devonian carbonate interval, SiSh=Silurian Clinton (Rose Hill) Shale.

Table 4.27. Wells used for the Tug Fork cross section. Record numbers can be used to view well data in the KGS Oil and Gas Database.

Permit No.	*Record No.*	*Well Name*	*County*	*Elevation (ft)*	*Total Depth (ft)*	*Formation at Total Depth*	*Samples*
17627	75304	Inland Gas 528 Wolfe	Boyd	848	3,372	Clinton Shale (Silurian)	
20876	2356	Inland Gas 535 McKeand	Boyd	852	9,449	Precambrian basement	X
44723	2350	Devon Energy 990 Hug	Boyd	680	3,292	Corniferous (Devonian)	
24502	11665	Inland Gas I 542 Young	Lawrence	865	12,712	Precambrian basement	X
78437	90998	CNR 1 Stuart	Lawrence	602	6,105	Beekmantown Dolomite (Ordovician)	X
25770	50748	Columbia Gas 9669 Pigg	Lawrence	704	3,680	Clinton Shale (Silurian)	X
24893	83097	CNR 9557T Fieger	Lawrence	799	4,037	Clinton Shale (Silurian)	X
89721	115976	Penn-Virginia Oil ATR-40 Penn-Virg.	Lawrence	1,031	3,049	Ohio Shale (Devonian)	
65202	45901	Meng 1 Copley	Martin	760	3,019	Ohio Shale (Devonian)	
870E8	13288	United Fuel Gas 8610T Jasper	Martin	647	13,172	Rome Formation (Cambrian)	
61674	32030	K V Oil & Gas MR252 Moore	Martin	850	3,544	Corniferous (Devonian)	X
79650	100771	Columbia Natural 21747 Pocahontas	Martin	1,313	6,263	Ohio Shale (Devonian)	X
96910	128265	GEOEX 4 Webb	Pike	1,195	4,131	Ohio Shale (Devonian	
82478	104509	Kinzer 6 Rogers Bros.	Pike	836	8,142	Knox Group (Ordovician)	X
90142	120104	Kinzer 874 Tugg Valley	Pike	980	4,344	Ohio Shale (Devonian)	
83031	105270	Ashland 1 Bonzo	Pike	1,347	5,150	Ohio Shale (Devonian)	X
97039	128384	Kinzer Drilling 1449 Cline	Pike	1,132	6,095	upper part of Ordovician	
94808	126080	Equitable 504806 Emperor Coal	Pike	937	4,380	Ohio Shale (Devonian)	X

upper part of the Rome. The Inland Gas Young well had shows of gas or oil and salt water in the Rome at depths of 8,530, 9,105, 9,160, 9,205, and 9,455 ft. There appear to be several thick porosity zones in Rome sands at depths of more than 8,500 ft in this well. The United Fuel Gas No. 8610T Jasper well encountered two porosity zones in the Rome. A show of gas was noted from 9,122 to 9,128 ft and a show of gas and salt water was reported at 9,189 ft. A drillstem test from 9,186 to 9,240 ft recovered 450 ft of gas-cut mud. A drillstem test across a broader interval from 9,049 to 9,484 ft recovered 6,800 ft^3 of gas and 400 ft of gas-cut mud.

Just west of the river (off the section) in Boyd County, the Inland Gas White well had a show of gas in the Rome at 7,445 ft and shows of oil and gas at 7,516 and 7,574 ft (Harris and Baranoski, 1996). Likewise, thick Rome sands have been encountered in Carter and Elliott Counties, 10 to 25 mi west of Tug Fork. Based on regional data, the area of thick Rome sandstones is relatively narrow and is likely limited to southern Boyd and northern Lawrence Counties (see “Rock Unit Summary”).

Conasauga Group. Three wells penetrated sandstones in the Maryville Formation of the Conasauga Group along this section (Fig. 4.80, Plate 4.8). In the United Fuels Gas No. 8610 Jasper well, there was a show of gas and water in the upper Maryville at 8,374 to 8,614 ft. No hydrocarbon or water shows were in the Inland Gas Young or Inland Gas McKeand wells, but at least the Inland Gas Young well had minor porosity development in the upper Maryville that might be related to the zone in the United Fuels Jasper well. More work would be needed to correlate this zone between deep wells in the area. Based on regional data, Harris and others (2004) inferred that only a small amount (10 percent or less) of sandstones in this interval was likely to have more than 4 percent porosity along Tug Fork, and that the sands were likely to be less well developed than to the west.

The Conasauga also contains appreciable thickness of shales, especially south of the Kentucky River Fault System. Where thick shales are present and unfaulted, they would likely provide an adequate seal to underlying injection in Rome sandstones or other deep reservoirs, if any are discovered.

Lower Knox–Copper Ridge Dolomite. The Copper Ridge was penetrated in three wells along the section (Fig. 4.80, Plate 4.8). In the Inland Gas No. 535 McKeand well, salt water was encountered at a depth of 6,425 ft in the middle of the Copper Ridge. Fracture porosity may also occur in the lower part of the unit in this well. To the south, in the Inland Gas No. I-542 Young well, no water was reported, but there are a few narrow porosity zones (possible fractures). Farther south, the United Fuel Gas No. 8610 Jasper well has no indications of porosity in the Copper Ridge. Whether this represents a trend of south-decreasing porosity in the lower Knox would require further research.

Rose Run Sandstone. The Rose Run is penetrated in four wells along this section (Fig. 4.80, Plate 4.8). Besides the three wells mentioned previously for underlying units, the Kinzer No. 6 Rogers Brothers well in Pike County may reach total depth in the Rose Run. No water or oil or gas shows were reported from these wells, although water was encountered just above or at the contact of the Rose Run and overlying Beekmantown in the Inland Gas No. 535 McKeand well (Boyd County). The Rose Run appears to thicken above the Rome Trough, and possibly to the south (Ryder and others, 1997), but has better porosity development to the west.

Upper Knox–Beekmantown Dolomite. The upper Knox is penetrated in five wells along this section (Fig. 4.80, Plate 4.8). In the Inland Gas No. 535 McKeand well, gas shows and salt water were encountered in the lower part of the Beekmantown at 5, 943 ft (300 ft from the top) and 6,030 ft (at the base, the contact with the Rose Run). Similar porosity zones appear to be developed in the Inland Gas No. I-542 Young well (according to density logs), although no water or gas have been reported. To the south, little evidence of porosity is in the lower or middle Beekmantown. A slight show of gas and water was at 6,735 ft in the United Fuel Gas No. 8610 Jasper well, 89 ft below the top of the Knox, but not in the other wells.

St. Peter Sandstone. Five wells penetrate the St. Peter along this section (Fig. 4.80, Plate 4.8). The three northern wells had shows of water or gas. All of these wells are along the northern margin of the Rome Trough. A slight show of gas was at 5,560 ft and water at 5,565 ft in the Inland Gas McKeand well. A show of gas with salt water was at the base of the St. Peter at 5,890 ft in the Inland Gas Young well and water was at 5,840 ft in the Columbia Natural Resources No. 1 Stuart well; similar porosity is indicated on the neutron log of the United Fuel Gas Jasper well (Martin County) from 6,636 to 6,643 ft. Hence, narrow bands of porosity are in most of the wells that penetrate this interval on the northern margin of the Rome Trough.

Regional data indicate that the St. Peter is irregularly distributed in the Rome Trough beneath the Tug Fork, with significant fault control on thickness (see "Rock Unit Summary"). The St. Peter is more than 160 ft thick south of the Kentucky River Fault System in southern Boyd and northern Lawrence Counties (Price, 1981; Humphreys and Watson, 1996), although it shows little evidence of porosity. Two wells have produced from the St. Peter west of Tug Fork. The Monitor Petroleum No. 1 Cecil Ison well (Stephens Field) in eastern Elliott County is located south of the Kentucky River Fault. Secondary fracture porosity is important in this field (Price, 1981; Humphreys and Watson, 1996). South of the Rome Trough the sandstone appears to thin (Ryder and others, 1997), and likely has little potential for storage.

Middle-Upper Ordovician Carbonates. This interval is penetrated by five wells along this section (Fig. 4.80, Plate 4.8). The top of the Lexington (Trenton) Limestone is at approximately 4,400 ft beneath sea level north of the Rome Trough, but is difficult to pick on geophysical logs. It deepens to more than 5,000 ft in the Rome Trough to the south. A show of gas was at 5,552 ft in the lower part of this interval (216 ft above the St. Peter) in the Inland Gas Young well (Lawrence County). Otherwise, density logs indicate mostly nonporous carbonates with a few isolated, narrow porosity zones, likely representing local fractures.

Upper Ordovician Shale. The top of the Upper Ordovician shale is difficult to distinguish from overlying Silurian shales in some geophysical logs, and the base is gradational with underlying carbonates in the

Trenton (Lexington) Limestone. The Upper Ordovician shale along this part of the river consists of interbedded limestone and shale and is more than 2,500 ft deep all along the river. Where the unit is unfaulted, and contains thick shales, it might provide an adequate seal to underlying injections.

Tuscarora (Clinton) Sandstone. Sandstones in the Clinton (Rose Hill) Shale interval are penetrated by nine wells along this section (Fig. 4.80, Plate 4.8). Thin (5 to 15 ft thick) sandstones occur in most of the wells in the northern part of the section. To the south, sandstones thicken to more than 50 ft, although they are variably interbedded with shale. In Lawrence County, Tuscarora (drillers' Clinton) gas was produced from a shaly interval at depths of 3,563 to 3,567 ft in the Columbia Gas Transmission No. 1 Pigg well. Also, water encountered at 3,580 ft in the Columbia Natural Resources No. 1 Stuart well appears to have been from a Clinton sandstone. An attempt was made to hydraulically fracture Clinton sandstones at depths of 3,941 to 3,954 ft in the Columbia Natural Resources No. 9557T Fieger, but no gas was encountered. Some porosity also appears to be in the Clinton sandstone at depths of 5,850 to 5,900 ft in the Kinzer Drilling Cline well. The same zone in the Kinzer Rogers Brothers well is significantly siltier (based on density logs), with less porosity, however. More work would be needed to examine wells to the east and west to determine the extent of porosity zones in this interval. There may be opportunities for carbon storage within sandstones in this interval as part of a stacked set of deeper reservoirs, but more work is needed to determine the thickness, composition, porosity, and continuity of sandstones within this interval.

Silurian Shale. The Silurian Rose Hill (Clinton) Shale is penetrated in nine wells along this section (Fig. 4.80, Plate 4.8). North of the Rome Trough, the shale is 200 ft thick and 2,800 to 3,200 ft deep. South of the faults the shale deepens to more than 5,500 ft. The shale should have good confining characteristics where it is thick and more than 2,500 ft deep on the east end of the section.

Keefer (Big Six) Sandstone. The Big Six is penetrated by 10 wells along this section (Fig. 4.80, Plate 4.8). In the Devon Energy Hug well, the hole was reported to have filled with water at 3,292 ft, which appears to be in the Big Six. Water shows were also reported in the Big Six (sometimes reported as lower Corniferous) in the Inland Gas Wolfe, Inland Gas McKeand, and Inland Gas Young wells. Minor porosity was also noted in the Columbia Natural Resources Fieger and Kinzer No. 6 Rogers wells. In Wayne County, W.Va., just across the river from Boone County, two fields have produced from the Keefer at depths of 2,700 to 2,900 ft. The Big Six is locally as much as 96 ft thick in these fields (Patchen, 1968a). Many wells just off of the line of section reach this interval and could be used for further evaluation.

Silurian-Devonian Carbonates. This entire interval is penetrated in 10 wells along this section, although the top is penetrated in at least three more wells (Fig. 4.80, Plate 4.8). Several wells show at least minor porosity development in this interval along Tug Fork. Minor Corniferous water ("damp") was reported in the lower Lockport/upper Big Six at a depth of 3,171 ft in the Inland Gas McKeand well (Boyd County), a show of gas in the Salina Formation at 3,020 ft, and a show of water in the Lockport at 3,230 ft in the Inland Gas Young well (Lawrence County). Many wells just off of the line of section reach this interval and could be used for further evaluation.

Oriskany Sandstone. The Oriskany is not widespread in eastern Kentucky (see "Rock Unit Summary"), but does occur in the United Fuel No. 8610T Jasper well in Martin County (no. 13288 in Figure 4.80, Plate 4.8). A show of sulfur-smelling gas was reported in the well from 2,882 to 2,888 ft. Sample descriptions indicate a limestone with fine-grained, subrounded sand grains. For this to represent a widespread porosity interval is unlikely, although exploration in the area for carbon storage would do well to examine any of the Corniferous units beneath the Devonian black shale in case secondary porosity is developed beneath the unconformity at the base of the black shale.

Devonian Shale. The Tug Fork section cuts across the Big Sandy Gas Field, the largest gas field in Kentucky. The field extends from southern Lawrence County to southern Pike County along Tug Fork. Production is from the Ohio Shale. Thousands of wells penetrate to the Devonian shale within the field, and in many wells along Tug Fork. Most of the wells along this section penetrate at least the upper part of the shale and several produce from the shale (Fig. 4.80, Plate 4.8). Along Tug Fork, the Devonian shale is 750 ft thick in Boyd County and thickens south and east to 1,700 ft in eastern Pike County. Depths to the top of the shale generally increase along a similar trend from 1,000 to 2,400 ft below sea level (Fulton, 1979). It might be possible to use CO_2 for enhanced gas recovery throughout this area, although more research is needed to prove the concept (Nuttall, 2006).

Shallower Porosity Horizons Deeper than 2,500 ft. Pennsylvanian quartzose sandstones are 150 ft thick on the northern end of the section, but thicken to more than 1,200 ft on the southern end. These sands are commonly associated with water and must be cased off when drilling. They are too shallow for miscible carbon storage (Fig. 4.80, Plate 4.8).

Numerous Mississippian units have been targets for oil and gas exploration along Tug Fork. In Pike County, in individual wells along the section, the Newman Limestone (drillers' Big Lime) is deeper than 2,500 ft. Because of the topography along the river, however, these units are not more than 2,500 ft beneath the river. The Big Lime produced at a depth of 2,772 to 2,778 ft in the Ashland No. 1 Bonzo well. The limestone reservoir was foam-fractured using water sand and nitrogen. Pressure and other testing data are available online in the KGS Oil and Gas Database. At shallower depths, minor porosity and a gas odor were encountered in the Big Lime at 2,400 ft in the Equitable 504806 Emperor Coal well. Also, the Berea Sandstone (at the top of the Devonian black shale sequence) is a gas producer in the Kinzer No. 874 Tug Valley well at depths of 3,075 to 3,138 ft. There may be opportunities for small-scale carbon storage or enhanced gas and oil recovery with carbon dioxide (rather than nitrogen) in the area. Large-scale storage, however, would have to take into consideration the many well penetrations into the underlying Devonian shale.

Coals Deeper than 1,000 ft. None are along this section.

Tug Fork Summary. Several potential carbon-storage reservoirs occur along Tug Fork. Most are concentrated along the northern stretch of the river in the northern part of the Rome Trough. In that area, there might be good possibilities for stacked reservoirs. A series of basement faults is also in this area, however, and any large-scale carbon storage project would likely have to evaluate whether specific faults were sealing or potential pathways for leakage.

Cambrian Rome sandstones occur at depths of 7,000 to 10,000 ft in a narrow belt in southern Boyd and northern Lawrence Counties. They appear to be thick with good porosity and have been shown to have significant porosity just west of Tug Fork in Elliott County. The Maryville sandstones of the Conasauga Group are also developed in the northern area, and possibly north of the Rome Trough in Boyd County as well. They are much thinner then the Rome sands but might cover a broader area. The Knox should be tested in any well that reaches the deeper potential horizons along Tug Fork, although the Knox has less indication of porosity along much of this river than in other parts of Kentucky. The St. Peter Sandstone is thick in the same area that the Rome sandstones are thick, and produced small amounts of water in several wells along the northern Tug Fork. The St. Peter Sandstone is known to thicken in fault blocks along the northern margin of the Rome Trough.

Younger potential reservoirs for at least small-scale carbon storage include the Clinton and Big Six sandstones, both of which have had water, oil, and gas shows beneath Tug Fork. Porosity has been found in these sands much farther south (into Pike County) than in the underlying St. Peter, Maryville, or Rome sandstones. Whether or not reservoirs are thick enough or extensive enough for large-scale carbon storage would require further research. There may be possibilities for stacking multiple reservoirs in some areas.

Much of the Tug Fork section is in the heart of the Big Sandy Gas Field. The Devonian shale is thick beneath the river, and there may be possibilities for enhanced gas recovery using carbon dioxide (see Nuttall, 2006), but more work is needed to test the injectivity of the shale. Several large oil and gas fields at depths of less than 2,500 ft have also had secondary recovery in the vicinity of Tug Fork. The Fallsburg Field is located on the river in northern Lewis County. At least eight large oil and gas fields are also on the Paint Creek Uplift in Elliott, Lawrence, Johnson, and Magoffin Counties, 25 mi west of Tug Fork. These fields are discussed in chapter 2.

Summary

The estimated capacity for CO_2 sequestration in Kentucky based upon DOE-sponsored phase I research findings is: (1) unmined coals, 0.31 to 0.43 billion short ton (0.28 to 0.39 billion metric ton) (NatCarb, 2008), (2) oil and gas reservoirs, 0.11 billion short ton (0.1 billion metric ton) (NatCarb, 2008), (3) saline reservoirs, 2.87 to 11.68 billion short tons (2.6 to 10.6 billion metric tons) (based on 1 percent and 4 percent capacity estimates of the Midwest Regional Carbon Sequestration Partnership and Midwest Geological Sequestration Consortium) (Table 4.28), and (4) hypothetically, in the Devonian shale, 25.1 billion short tons (22.8 billion metric tons) (Nuttall and others, 2005).

The total estimated capacity for unmined coals, oil and gas reservoirs, and saline reservoirs in Kentucky is 3.29 to 12.22 billion short tons (2.98 to 11.09 billion metric tons), and saline reservoirs account for 88 to 96 percent of the total. If the Devonian shale capacity can be realized, then storage capacity might be as much as 37.32 billion short tons (33.89 billion metric tons).

For comparison, a 500-MW, bituminous-coal-fired power plant produces 2.2 to 4.4 million short tons (2 to 4 million metric tons) of CO_2 a year, and in 2005, Kentucky produced 169,053 million short tons (153.8 million metric tons) of CO_2, of which 102.84 million short tons (93.3 million metric tons) (61 percent) was from coal-fired power plants (Energy Information Administration, 2008).

The fact that there may be tens of billion of tons of storage capacity and only millions of tons of annual emissions indicates that Kentucky, has the theoretical capacity to store hundreds of years worth of CO_2 emissions. Not all areas of the state have equal opportunities for industrial-scale carbon sequestration, however, and the economics of storage will not be equivalent for all units in all areas.

Because the greatest potential for carbon storage is in deep saline reservoirs, this investigation characterized deep saline reservoirs and their sealing/confining units. Qualitative and quantitative data for potential deep saline reservoirs have been provided for each of the units and summarized in Table 4.28. The preceding lengthy discussion of the CO_2 storage characteristics of the rock units provides critical background material for evaluation of Kentucky's carbon-storage potential, especially along the state's major river-industrial corridors.

1. Fourteen regional thickness maps and eight regional cross sections show that potential reservoirs and their confining intervals are not equally distributed around the state, varying in depth, thickness, and distribution.
2. Storage capacity estimates for seven deep sandstones in the state (Table 4.28) indicate that Kentucky has potential saline aquifer storage capacity of 2.9 to 11.7 billion short tons (2.6 to 10.6 billion metric tons) (at 1 percent and 4 percent capacity), half of which is in the Mount Simon Sandstone.
3. The Mount Simon Sandstone is restricted mostly to the Ohio River area in the western and central part of the state, and is thinner and less porous than in the central Illinois Basin. This study indicates that the conservative capacity estimate is likely more appropriate, because the lateral extent of the sandstone is less than previously thought, and also because west of Hancock County, the sandstone is more than 7,000 ft deep and estimated to have reduced porosity. The recent CO_2 injection demonstration well in Boone County will provide data to demonstrate the feasibility of using the Mount Simon in northern Kentucky.
4. Sandstone in the Rome Formation in eastern Kentucky is the state's only other sandstone aquifer that exceeds 100 ft in thickness. This interval has known porosity and permeability, but is restricted to a narrow belt along the Kentucky River Fault System. It has storage potential, but proximity to faults may raise concerns about leakage. Conflicts with leases for gas exploration are also possible.
5. The St. Peter Sandstone has broad distribution in Kentucky, but is generally thin, is irregularly distributed, and has variable porosity and thickness. The thickest St. Peter Sandstone is along fault blocks of the Kentucky River Fault System in eastern Kentucky. Structural traps are possible, although proximity to faults may raise concerns about leakage.
6. All other traditional sandstone saline reservoirs in the state are thin relative to large-scale carbon storage, generally less than 30 ft, but several could be used as part of stacked reservoir scenarios. This will be more difficult than using a single, thick, porous reservoir, but may be possible in some areas.
7. The Knox carbonates underlie the entire state and have known porosity where shallow. No quantitative evaluation of capacity is possible at this time, because carbonate reservoirs such as the Knox are generally more variable than the regional sandstone aquifers generally considered in regional carbon sequestration studies. The Knox has been used for waste injection in Louisville and Butler County. Porous zones are thin, but multiple zones and

Table 4.28. Estimated storage capacities of saline reservoirs in eastern and western Kentucky based on phase I results of the Midwest Regional Carbon Sequestration Partnership for eastern Kentucky (Wickstrom and others, 2005) and Midwest Geological Sequestration Consortium for western Kentucky (Frailey and others, 2005).

Saline Reservoir	*Estimated Storage Capacity in Billion Short Tons (Billion Metric Tons)*					
	Eastern Kentucky	*4 Percent*	*1 Percent*	*Western Kentucky*	*4 Percent*	*1 Percent*
Mount Simon Sandstone	47.8 (43.4)	1.9 (1.7)	0.5 (0.4)	154 (140)*	6.3 (5.7)*	1.5 (1.4)*
Rose Run Sandstone	60.0 (54.4)	2.4 (2.2)	0.6 (0.5)	0	0	0
Rome Sandstone	11 (10)	0.4 (0.4)	0.1 (0.1)	0	0	0
St. Peter Sandstone	–	–	–	11 (10)	0.7 (0.6)	0.1 (0.1)
Tuscarora Sandstone	0.98 (0.89)	0.04 (0.04)	0.01 (0.009)	0	0	0
Oriskany Sandstone	0.02 (0.02)	0.0009 (0.0008)	0.0002 (0.0002)	0	0	0
Conasauga sandstones	0.02 (0.02)	0.007 (0.0006)	0.001 (0.0001)	0	0	0
Eastern and Western Kentucky subtotals		4.7 (4.3)	1.2 (1.1)		6.9 (6.3)	1.7 (1.5)
Total Kentucky					11.7 (10.6)	2.9 (2.6)

saline water are encountered in many areas. The recent small-scale CO_2 demonstration test in Hancock County was successful. Further research is planned in this well. Data will provide insight into the possibilities of using the Knox as a storage reservoir.

8. Nuttall and others (2005) have estimated that the Devonian shale has the capacity to store more than 25 billion short tons (22.8 billion metric tons) of CO_2. This is still a theoretical technology, but testing in the near future in eastern Kentucky may help show whether the shale, which is widespread in Kentucky, could be used for storage or only for enhanced gas recovery, in which case total CO_2 storage would likely be significantly less.
9. Cross sections below the state's major rivers show the depths to potential reservoir intervals and confining layers to help evaluate the carbon-storage potential beneath these industrial corridors.

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Chapter 5: Site Bank Assessment Geologic Data Report, Round 2, 2008

Brandon C. Nuttall, David C. Harris, John B. Hickman, and Michael P. Solis

The coal industry is important to Kentucky as a source of jobs, revenue, and electric-power generation. Current technology and the likelihood of a carbon-emissions-constrained future suggest the state needs to be proactive in identifying candidate sites for industrial development that include the potential for local, long-term carbon storage (sequestration). The Commonwealth of Kentucky requested nominations of potential locations for development of coal to liquids or integrated gasification combined-cycle electricity-generating utilities and requested an assessment of carbon-storage possibilities. Nineteen original sites were proposed and assessed in October 2007; these sites are superficially addressed in this report. In December 2007, an additional 26 sites were nominated for evaluation and inclusion in the site bank discussed in this report. Of the 26 sites nominated for this assessment, three were not evaluated because of lack of location data (assumed withdrawn). Twenty-three sites were evaluated by the Kentucky Geological Survey to assess geologic criteria for storage potential for the sites (Fig. 5.1). Sites 2.06 and 2.25 are substantially similar to the previously nominated sites “R” and “F,” respectively.

In general, most sites have a potential for carbon storage in at least one deep saline reservoir, often the Ordovician Knox Formation. In addition, other deep formations often underlie a site, but the lack of specific and detailed subsurface and reservoir data constrain primary reliance on these zones. For Knox reservoirs, the primary seal is likely the impermeable carbonates of the Knox itself and Middle and Upper Ordovician shales (Maquoketa). The Devonian New Albany, Ohio, and Chattanooga black shales represent a secondary seal across much of the state.

Final site scores will include nongeologic factors evaluated by other contractors (transportation network, electricity and gas transmission, water supply and transportation issues, and other factors). This report does not incorporate those final scores.

Evaluation Process

Geospatial analysis was accomplished with ArcMap, a geographic information system software from ESRI. Buffers with radii of 5, 10, 15, and 20 mi were constructed for each nominated site to represent various areas of review. For the 10-, 15-, and 20-mi radii, the Kentucky portion of the area enclosed by the circle was determined. Sites with substantial portions of their areas of review in surrounding states will require interstate assessments for which the Kentucky Geologi-

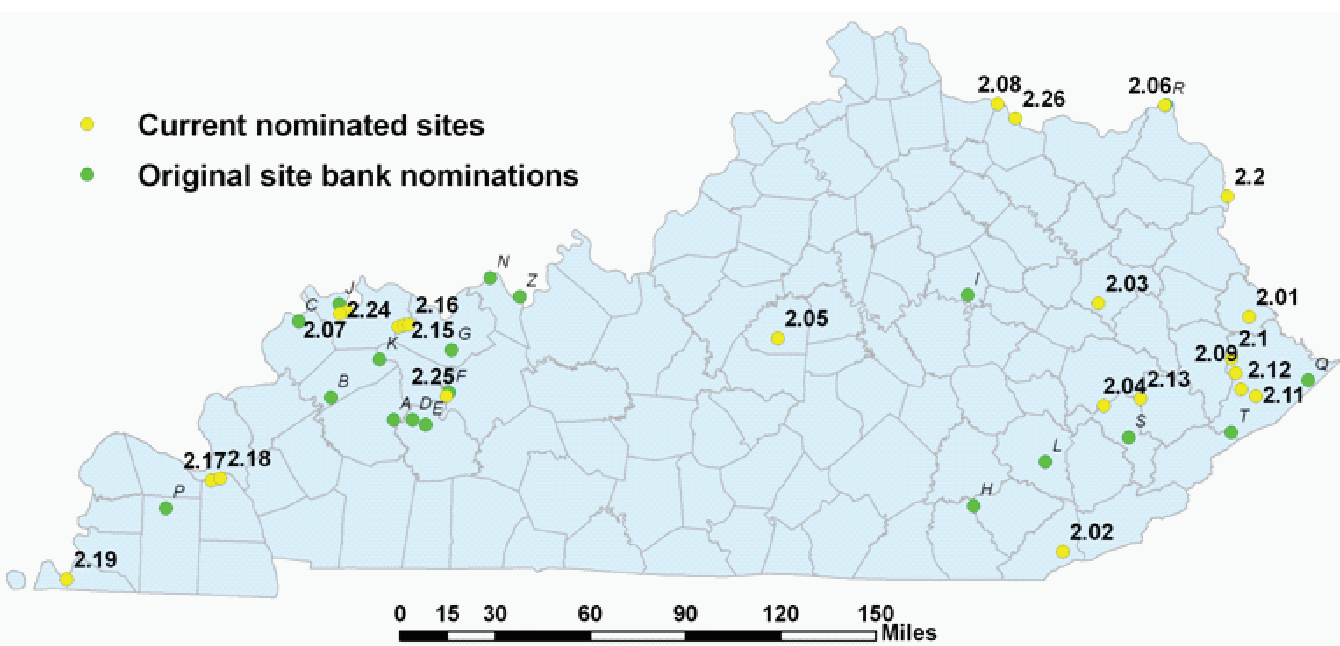

Figure 5.1. Locations of proposed sites.

cal Survey lacks sufficient data. Table 5.1 summarizes the percentage of each area of review that lies within Kentucky.

For each site, a location map was compiled to show the proposed site bounded by a 15-mi area of review. The maps show surface faults mapped at 1:24,000 scale and the oil (green shading) and gas (red shading) fields (Fig. 5.2). Individual well locations are shown where the existing oil and gas field outlines do not adequately represent recent oil and gas development or where well data are sparse. Wellbores may represent potential leakage pathways for stored CO_2 to be released to the surface. To qualitatively assess this potential, two stratigraphic intervals were selected: the Devonian black shale (Ohio–Chattanooga–New Albany), a regional seal and potential storage target; and the Ordovician Knox Dolomite, a potential regional deep saline reservoir. Figure 5.3 is an example histogram showing total depth for oil and gas wells within 10 mi of the nominated Martiki site (shown in Figure 5.2). The histogram also shows the distribution of penetrations with respect to the average depth to the top of the Devonian shale (red line) and Knox Dolomite (green line). To facilitate a future site-specific assessment, the existing deep wells were identified and reported.

Potential storage zones for each site were identified by compiling a series of structure maps showing the elevation of the Precambrian basement, Cambrian Mount Simon and Rome Sandstones, Cambrian-Ordovician Knox carbonates, Ordovician Rose Run and St. Peter Sandstones, Devonian Ohio–Chattanooga–New Albany black shale, and deep Pennsylvanian coals (assumed unmineable), in feet with respect to sea level. For example, the structure map on top of the Mount Simon in Figure 5.4 suggests that the Mount Simon is absent at the Martiki site. Other reservoir and seal intervals for each site are summarized in Table 5.2. The availability of nearby seismic-reflection survey data for investigation of the deep geology was considered in the assessment, although no seismic data were interpreted.

Table 5.1. Percentage of area of review in Kentucky for each site.

Site ID	*5 mi %*	*10 mi %*	*15 mi %*	*20 mi %*
2.01	100	88	76	71
2.02	95	78	70	64
2.03	100	100	100	100
2.04	100	100	100	100
2.05	100	100	100	100
2.06	44	32	28	28
2.07	83	81	74	66
2.08	51	44	42	45
2.09	100	100	100	99
2.10	100	100	100	99
2.11	100	100	86	77
2.12	100	100	98	89
2.13	100	100	100	100
2.14	100	100	90	79
2.15	100	99	86	77
2.16	100	97	84	77
2.17	97	87	86	86
2.18	100	91	88	88
2.19	67	49	37	33
2.20	44	44	43	44
2.24	93	81	74	67
2.25	100	100	100	100
2.26	51	53	56	56

Figure 5.5 is an earthquake hazards map based on expected peak ground acceleration (g) with 10 percent probability of being exceeded in 50 yr (U.S. Geological Survey, 2008).The peak ground acceleration is an indicator of the shaking force that a surface structure (pipeline, coal-to-liquids plant, or other facility) might experience with a given probability (10 percent) over a specified time. The expected hazard at a particular site increases with increasing ground motion, increasing probability of occurrence, and decreasing time intervals. It should be noted that the 2008 U.S. Geological Survey hazard model was used to maintain consistency with earlier site-bank assessments; new earthquake hazard assessments and seismic risk maps are being compiled by the Kentucky Geological Survey (Wang, 2009).

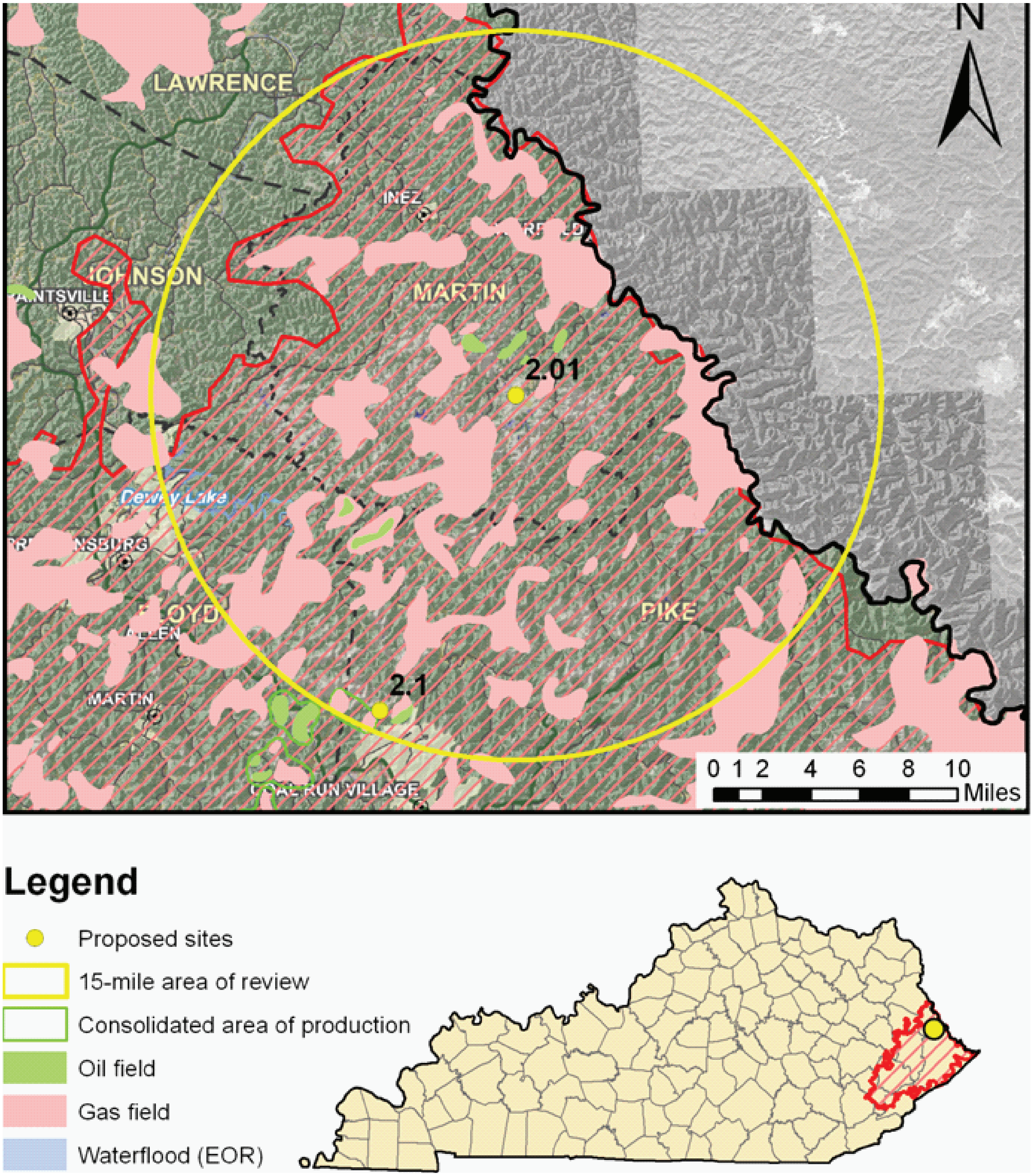

Figure 5.2. Location of site 2.01, Martiki, showing oil and gas fields in vicinity.

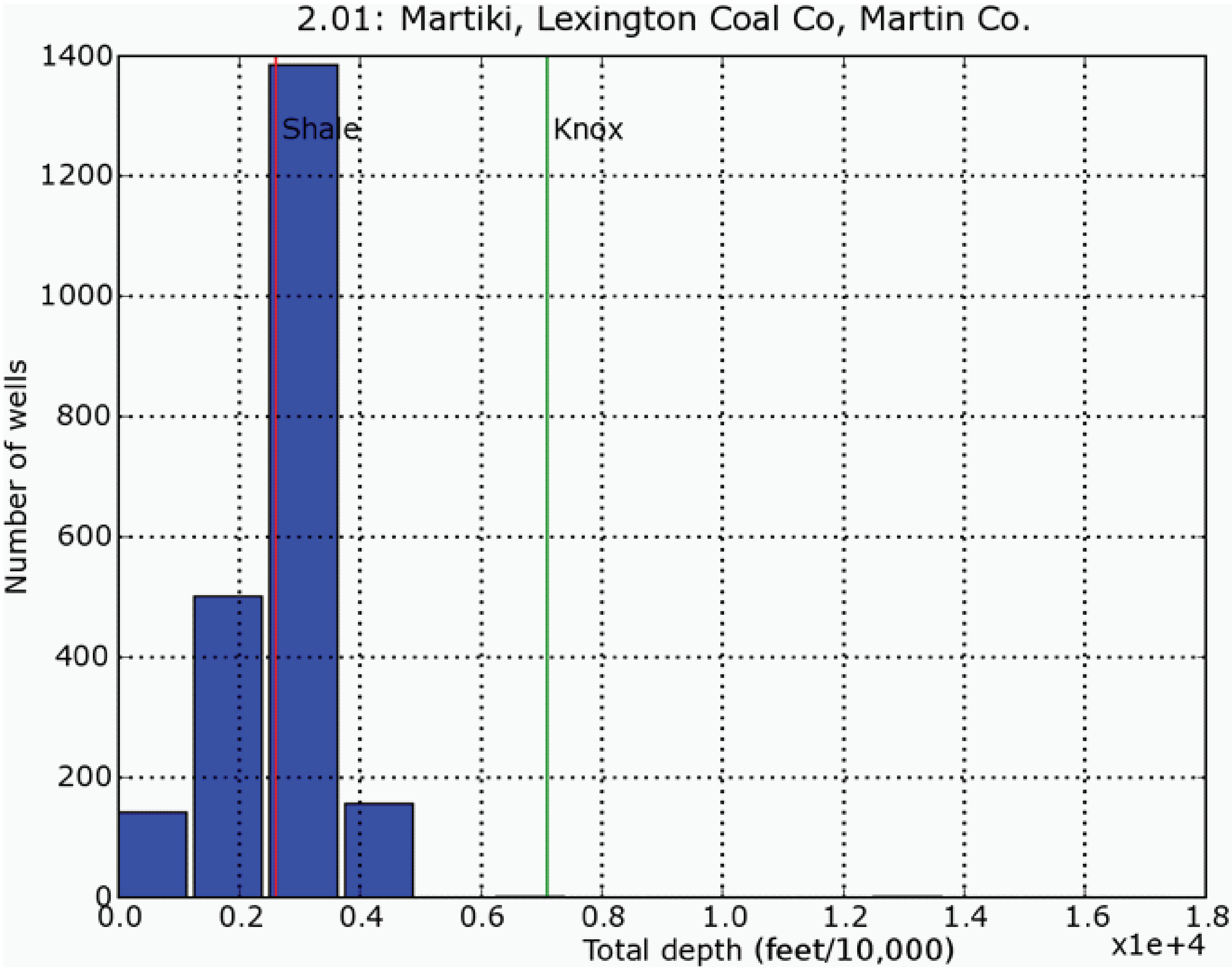

Figure 5.3. Histogram of total depth for oil and gas wells within 10 mi of the Martiki site (Fig. 5.2).

A decision matrix for scoring and ranking sites was compiled. Table 5.3 shows the criteria, the definition, and scoring rationale for ranking each of the sites. For each site, additional criteria were assessed by staff of the Smith Management Group, and the overall site scores will be included in their final report and are not provided here.

Summary

- Kentucky has a selection of sites across the state that have the potential for geologic storage of CO_2.
- Key assessment parameters include the proximity to earthquake hazard areas and the likelihood of deep saline reservoirs underlying or within a reasonable distance of the site.
- Proposed sites along Kentucky's borders require additional assessment details to incorporate interstate data.
- A full site assessment includes a variety of infrastructure and environmental factors not included in this geologic assessment. See the complete site bank assessment reports online:
  - August 2007, www.energy.ky.gov/NR/rdonlyres/05D4C7EA-51A9-4034-9021-A526A850F2FA/0/SiteBankReport.pdf (sites not addressed in this current report)
  - June 2008, www.energy.ky.gov/NR/rdonlyres/4CEFFE45-23D2-4BA6-AB48-473ADC00D582/0/SiteBankII.pdf (sites addressed in this report)

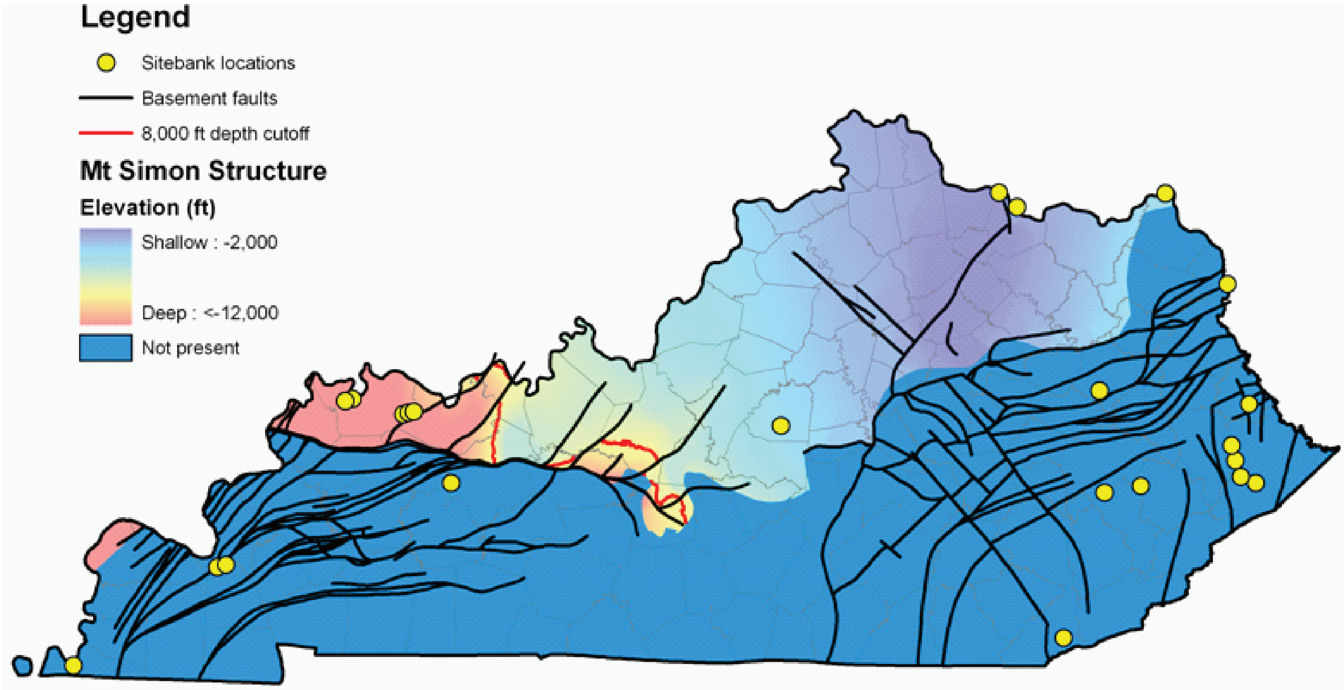

Figure 5.4. Structure on the top of the Cambrian Mount Simon Sandstone (preliminary), a potential deep saline reservoir, showing the 8,000-ft drilling-depth cutoff.

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Table 5.2. Deep saline reservoirs, primary storage targets, and primary seals that underlie proposed sites.

ID	*Company*	*Site*	*County*	*Basal Sand*	*Mount Simon*	*Rome, Conasauga, Eau Claire*	*Rose Run*	*Knox*	*St. Peter*	*Primary Seal*	*Wells Through Seal*	*Seismic Line*	*Average Top of Devonian Shale*	*Average Top of Knox*
2.01	Lexington Coal Co.	Martiki	Martin	yes	absent	yes	yes	**primary**	yes	Black River, Ordovician shales	1	none	2,600	7,100
2.02	Cumberland Valley Area Develop-ment District	Pine Mountain Regional Industrial Park	Bell	absent	absent	?	yes	**primary**	absent	Black River, Ordovician shales	8	none	3,500 (ap-proximate base of thrust sheet)	6,600
2.03	Morgan County Gov-ernment	Ky. 205 & Mountain Parkway.	Morgan	< 10% sand-stone with > 4% porosity	absent	yes	yes	**primary**	yes	Black River, Ordovician shales	22	31-1a	1,200	3,600
2.04	Pine Branch Coal Sales	Pine Branch	Perry	< 10% sand-stone with > 4% porosity	absent	yes	yes	**primary**	yes	Black River, Ordovician shales	5	31-1b	2,300	5,100
2.05	Hal Goode	Spring-field-Wash-ington County Com-merce Center	Washing-ton	absent	**primary**	yes	yes	**primary**	absent	Black River, Ordovician shales	4	none	shale not present in subsur-face	1,200
2.06	George Ar-rington	South Shore	Greenup	absent	**primary**	yes	yes	yes	?	Conasauga	1	none	450	3,200
2.07	Henderson County Port Authority	Hen-derson County Riverport	Hender-son	absent	yes	yes	absent	**primary**	yes	Maquoketa, Black River	0	231	4,100	8,200
2.08	Maysville-Mason County In-dustrial De-velopment Authority	Dover, Ky., industrial site	Mason	absent	**primary**	yes	yes	yes	absent	Black River, Ordovician shales	2	none	shale not present in subsur-face	1,100

Table 5.2. Deep saline reservoirs, primary storage targets, and primary seals that underlie proposed sites.

ID	*Company*	*Site*	*County*	*Basal Sand*	*Mount Simon*	*Rome, Conasauga, Eau Claire*	*Rose Run*	*Knox*	*St. Peter*	*Primary Seal*	*Wells Through Seal*	*Seismic Line*	*Average Top of Devonian Shale*	*Average Top of Knox*
2.09	Summit Engineering Inc.	Big Shoal	Pike	< 10% sand-stone with > 4% porosity	absent	yes	yes	**primary**	yes	Black River, Ordovician shales	3	none	3,000	6,700
2.10	Summit Engineering Inc.	airport	Pike	yes?	absent	yes	yes	**primary**	yes	Black River, Ordovician shales	3	none	2,800	6,700
2.11	Summit Engineering Inc.	Hopkins Branch	Pike	< 10% sand-stone with > 4% porosity	absent	yes	yes	**primary**	absent	Black River, Ordovician shales	2	none	3,200	7,200
2.12	Summit Engineering Inc.	Marion Branch	Pike	< 10% sand-stone with > 4% porosity	absent	yes	yes	**primary**	absent	Black River, Ordovician shales	2	none	2,900	7,200
2.13	Summit Engineering Inc.	Knott County Industrial	Knott	< 10% sand-stone with > 4% porosity	absent	yes	yes	**primary**	yes	Black River, Ordovician shales	1	none	2,600	5,550
2.14	Penn Virgin-ia Resource Partners	Area A	Hender-son	absent	yes	yes	absent	**primary**	yes	Maquoketa, Black River	0	FAY-635, FAY-639, FAY-640	3,700	6,900
2.15	Penn Virgin-ia Resource Partners	Area B	Hender-son	absent	yes	yes	absent	**primary**	yes	Maquoketa, Black River	0	FAY-635, FAY-640	3,700	6,500
2.16	Penn Virgin-ia Resource Partners	Area C	Hender-son	absent	yes	yes	absent	**primary**	yes	Maquoketa, Black River	0	FAY-635, FAY-640	3,500	6,000
2.17	Mike Miller	Marshall County–Calvert City	Marshall	?	absent	yes	absent	**primary**	yes	Maquoketa, Black River	2	none	800	4,700
2.18	Bailey Port Inc.	Bailey Port	Marshall	?	absent	yes	absent	**primary**	yes	Maquoketa, Black River	1	none	800	4,700

Table 5.2. Deep saline reservoirs, primary storage targets, and primary seals that underlie proposed sites.

ID	*Company*	*Site*	*County*	*Basal Sand*	*Mount Simon*	*Rome, Conasauga, Eau Claire*	*Rose Run*	*Knox*	*St. Peter*	*Primary Seal*	*Wells Through Seal*	*Seismic Line*	*Average Top of Devonian Shale*	*Average Top of Knox*
2.19[1]	Tennessee Valley Authority	Hickman Property	Fulton	?	absent	yes	absent	**primary?**	absent	Knox carbonates?	3	DOW-2, DOW-2a	shale not present in subsurface	1,950
2.20	George Arrington General Coal Services, LLC	Big Sandy River	Boyd	yes	**primary**	yes	yes	yes	yes	Black River, Ordovician shales	5	N43D-1	1,900	5,700
2.21	Greater Owensboro Economic Development Corp.	Addison	Breckinridge	not assessed; no location provided										
2.22	Greater Owensboro Economic Development Corp.	Newman	Daviess	not assessed; no location provided										
2.23	Greater Owensboro Economic Development Corp.	W.R. Grace at Baskett	Henderson	not assessed; no location provided										
2.24	Greater Owensboro Economic Development Corp.	Tri-State at Geneva	Henderson	absent	yes	yes	absent	**primary**	yes	Maquoketa, Black River	0	none	4,200	8,000
2.25	Green River Area Development District	Big Rivers	Ohio	absent	yes	yes	absent	**primary**	**yes**	Maquoketa, Black River	6	IBK-92	3,000	6,200
2.26	Maysville–Mason County Industrial Development Authority	Maysville	Mason	absent	**primary**	yes	yes	yes	absent	Black River, Ordovician shales	3	none	shale not present in subsurface	900

[1]As of the date of this report, there were insufficient subsurface data (boreholes) to project potential storage and seals below the Ordovician Knox Formation for site 2.19, Fulton County. Interpretation of available seismic data was beyond the scope of this assessment

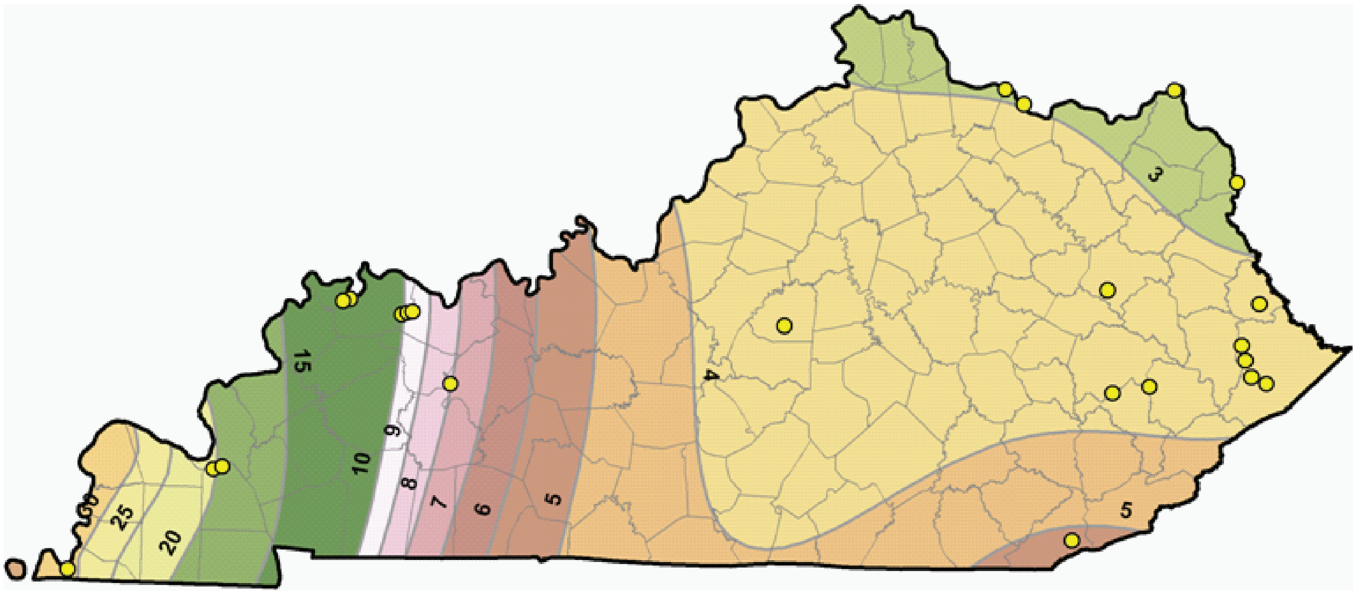

Figure 5.5. Earthquake hazard map of Kentucky showing expected ground acceleration (g) with 10 percent probability of being exceeded in 50 yr (U.S. Geological Survey, 2008).

Table 5.3. Criteria description and scoring used in decision matrix for site assessment.

Criteria	*Description*	*Qualifying Criteria*	*Rationale for Criteria*
2.1	Seismic stability	The proposed site must have low risk from significant seismic events. Proven by supporting geologic data and calculations demonstrating peak ground acceleration less than 20 percent g, with a 10 percent chance of being exceeded in 50 yr. Peak ground acceleration is the most appropriate seismic-hazard criterion because of pipeline infrastructure and other shallow subsurface facilities associated with the Site Bank Project. MCE indicates the maximum credible earthquake and is defined as included in this discussion.	See seismic risk map. 5–0.05 g MCE 4–0.10 g MCE 3–0.20 g MCE 0–0.30 g MCE 0–0.50 g MCE
2.2.1	Oil fields (immiscible EOR potential)	One or more oil fields within 20 mi and less than 2,500 ft depth.	CO_2 injection is a demonstrated technology for enhanced oil recovery. Storage of CO_2 when combined with recovery of additional resources is mutually beneficial. 5–One or more oil fields within 20 mi and less than 2,500 ft depth 0–No oil fields within 20 mi and less than 2,500 ft depth

Table 5.3. Criteria description and scoring used in decision matrix for site assessment.

Criteria	*Description*	*Qualifying Criteria*	*Rationale for Criteria*
2.2.2	Oil fields (miscible EOR potential)	One or more oil fields within 20 mi and 2,500 ft or more in depth.	CO_2 injection is a demonstrated technology for enhanced oil recovery. Storage of CO_2 when combined with recovery of additional resources is mutually beneficial. Miscible flooding operations using supercritical CO_2 will sequester greater quantities of carbon than gaseous (immiscible) projects because of the density difference. 5 – One or more oil fields within 20 mi and greater than 2,500 ft depth 0 – No oil fields within 20 mi and greater than 2,500 ft depth
2.2.3	Proximity to proposed target formation	Although it is not necessary for the target formation to immediately underlie the proposed site for the Site Bank Project facility, it should be close to the proposed site in order to facilitate construction of pipelines or reduce transportation costs. It is preferable for cost and construction considerations for the proposed site and the proposed target formation to be as close to each other as possible.	5 – Target formation beneath proposed plant site 3 – Target formation within 5 mi 1 – Target formation farther than 5 mi
2.3	Other geologic factors	Comment on other geologic factors that might influence the site.	
2.3.1	Faults	Presence of mapped fault(s) within 10 mi.	Faults can be transmissive or sealing and will require further investigation. 5 – No faults within 10 mi 0 – Fault(s) within 10 mi of the site
2.3.2	Organic-rich black shale (speculative)	Known shale gas production within 10 mi, at depths of more than 1,000 ft.	In addition to acting as a reservoir seal, gas-prone areas of shale (particularly the Devonian Ohio–New Albany–Chattanooga black shale) preferentially adsorb CO_2, potentially displacing natural gas. This may provide a method of offsetting the cost of storage using enhanced gas recovery. 5 – Deep shale gas production within 10 mi 0 – No deep shale gas production within 10 mi
2.3.3	Unmineable coals	Known coal beds within 10 mi, at depths of more than 1,000 ft.	CO_2 injection into coals for enhanced coalbed methane (natural gas) recovery has been demonstrated. This may provide a method of offsetting the cost of storage using enhanced gas recovery. 5 – Deep coal beds within 10 mi 0 – No deep coal beds within 10 mi

Table 5.3. Criteria description and scoring used in decision matrix for site assessment.

Criteria	*Description*	*Qualifying Criteria*	*Rationale for Criteria*
A 2.1	Deep saline reservoir (proven)	Well or core *within 1 mi* of the proposed site that demonstrates suitable thickness, porosity, and permeability, that is 2,500 to 10,000 ft in depth, and has at least one demonstrated overlying seal at least 20 ft thick.	Current best practice indicates that deep saline formations are likely to have the largest capacity for long-term storage of CO_2 as a supercritical fluid. This criteria is intended to demonstrate the presence and utility of such a zone in the immediate vicinity of the proposed site. 5 – Well or core within 1 mi 0 – No well or core within 1 mi
A 2.2	Deep saline reservoir (probable)	A well or core that is *1 to 15 mi* away from the proposed site demonstrates the likelihood of suitable porosity or permeability between 2,500 and 10,000 ft depth and indicates 20 ft or more of impermeable seals in the overlying strata.	Current best practice indicates that deep saline formations are likely to have the largest capacity for long-term storage of CO_2 as a supercritical fluid. This criteria is intended to indicate the probable presence and utility of such a zone as demonstrated by one or more wells a reasonable distance from the proposed site. 5 – Well or core between 1 and 15 mi 0 – No well or core between 1 and 15 mi
A 2.3	Deep saline reservoir (speculative)	A well or core that is *15 to 25 mi* away from the proposed site indicates that a porous and permeable zone between 2,500 and 10,000 ft depth and with 20 ft or more of impermeable seals in the overlying strata can be inferred to be underlying the proposed site.	Current best practice indicates that deep saline formations are likely to have the largest capacity for long-term storage of CO_2. This criteria is intended to indicate the presence of such a zone is likely, but no well data within a reasonable distance from the proposed site are available on which to base an assessment. 5 – Well or core within 15 to 25 mi 0 – No well or core within 15 to 25 mi
A 2.4	Demonstrated closure	Sufficient data to show structural closure on primary saline reservoir target *within 15 mi*	Current best practice indicates the presence of a structural closure will limit migration of injected CO_2. 5 – Structural closure on primary target 0 – Insufficient closure on primary target
A 2.5	Multiple deep saline reservoirs	Two or more *proven* or *probable* saline reservoirs as defined above.	Multiple stacked intervals increases the likelihood of sufficient capacity for storage. 5 – Two or more saline reservoirs 0 – Fewer than two saline reservoirs
A 2.6	Demonstrated closure	Sufficient data to show structural closure on one or more of the available oil reservoirs for storage (miscible or immiscible) *within 15 mi.*	Structural closure will limit migration of injected CO_2. Additional analysis is required to determine the volume of the closure to its spill point. 5 – One or more available reservoirs 0 – No structural closure on available reservoirs

Table 5.3. Criteria description and scoring used in decision matrix for site assessment.

Criteria	*Description*	*Qualifying Criteria*	*Rationale for Criteria*
A 2.7	Subsurface activity/ access	The presence of oil and gas fields, underground coal mines, or limestone/aggregate quarries within *10 mi.*	Need to assess potential issues with respect to mining health and safety, ownership and leases of the mineral estate, and potential subsurface access conflicts. 5 – No sites within 10 mi 0 – Sites within 10 mi
A 2.8	Well penetrations into primary seal	Number of penetrations through the primary seal of the main target formation within a *10-mi area of review.*	Wellbores represent potential migration pathways for CO_2 leakage into underground sources of drinking water or to the surface. Need to assess integrity of the seal with respect to the density (number) of wellbores, their depths, and the possibility of unlocated holes to ensure CO_2 does not leak. 5 – Zero to three well penetrations within 10 mi 3 – Three to six well penetrations within 10 mi 0 – More than six well penetrations within 10 mi
A 2.9	Availability of seismic-reflection data	Seismic lines within *5 mi* of the site	Seismic-reflection data are essential for use in assessing the nature and potential integrity of a unit for storage and modeling the geometry of the area of pore space to be contacted by CO_2. 1 – Seismic lines available within 5 mi 0 – No seismic lines available within 5 mi

Appendix A: Geologic Data Sources

Stephen F. Greb, James A. Drahovzal, and Thomas N. Sparks

Broad ranges of geologic data are necessary to evaluate potential geologic CO_2 storage sites. The supplementary information in this appendix describes the types of data and various sources for obtaining these data. Many of the geologic data used for evaluating CO_2 storage are available at the Kentucky Geological Survey Web site: www.uky.edu/KGS/.

Geologic Data Sources

The principal data needed to calculate gross storage capacity for potential sequestration reservoirs are the porosity, thickness, area, temperature, and pressure of the reservoir, and salinity of interstitial fluids. The amount of irreducible water also needs to be considered, which is typically only estimated with numerical modeling. A similar calculation can be made for carbon storage in oil and gas reservoirs. It is important to note that these calculations provide a maximum theoretical capacity, and the practical capacity will be further reduced (Bachu and others, 2007). An example of an online calculator is provided through the NatCarb Web site: www.natcarb.org/Calculators/.

For large-scale, industrial geologic storage of carbon dioxide, storage rates of 1 million metric tons per year may be needed, which will require very large reservoirs (much larger than existing oil fields), or multiple smaller reservoirs. Exploring for these reservoirs will not be easy and will require different types of data. The primary source will come from wellbores used for oil and gas exploration. Seismic data will also be important for correlating units away from known oil and gas wells, or at depths greater than are penetrated by local oil and gas wells, and for determining if there are faults at depths that could serve as pathways for leakage of injected CO_2. Regulations have not been promulgated yet for large-scale storage of CO_2 in the United States, but the Environmental Protection Agency is in the process of writing them (U.S. EPA, 2008a, b). Until these regulations are written, the best estimates of the types of geologic data that will be needed to permit future storage projects are the permits for the current DOE phase II demonstration projects.

Oil and Gas Data

The type of data that might be generated during or after drilling of an oil and gas exploitation well include downhole geophysical logs (density, gamma ray, etc.) to determine rock type, rock unit correlations, depths, and porosity. In addition, samples of rock cuttings, and in some cases cores, are sometimes collected for evaluating rock mineralogy, porosity, and permeability. In some cases, reservoir tests are conducted, which include information about reservoir pressure. Also, fluid samples can be taken to determine hydrocarbon (gas, oil) composition and water composition (salinity, chemistry). A significant amount of oil and gas well data has been used to generate databases, maps, and summary reports for the phase I regional characterization studies of the DOE-sponsored MGSC (Frailey and others, 2005) and MRCSP (Wickstrom and others, 2005). Much of the data for the phase I report pertinent to Kentucky was obtained from the KGS Oil and Gas Database (kgsweb.uky.edu/DataSearching/oilsearch.asp).

More than 160,000 oil and gas wells have been drilled in Kentucky, although their locations are not evenly distributed around the state (Fig. A.1). These wells represent a wealth of subsurface data, although most of the wells are relatively shallow (less than 1,500 ft) and have limited usefulness for deep CO_2 storage research. For deeper analysis, 4,047 wells penetrate 4,000 feet or deeper (Fig. A.2). From a carbon storage perspective, this is both good and bad. Fewer wells mean fewer penetrations and therefore less information about potential storage and seal formations. Well penetrations, however, are one of the primary pathways for potential leakage of injected CO_2, so fewer penetrations reduce the risk of leakage. Documenting the number of well penetrations in the proposed area of influence was one of the criteria required in the FutureGen proposals, and will likely be required in any future CO_2 storage project.

Seismic Data

All of the phase II demonstration projects for the DOE-sponsored regional carbon sequestration partnerships have included seismic lines at their test sites as part of their applications for EPA Class V experimental injection permits. Seismic data are useful for correlations and depth projections of rock units in the deep subsurface. They are also useful for determining the dip of beds and the presence or absence of struc-

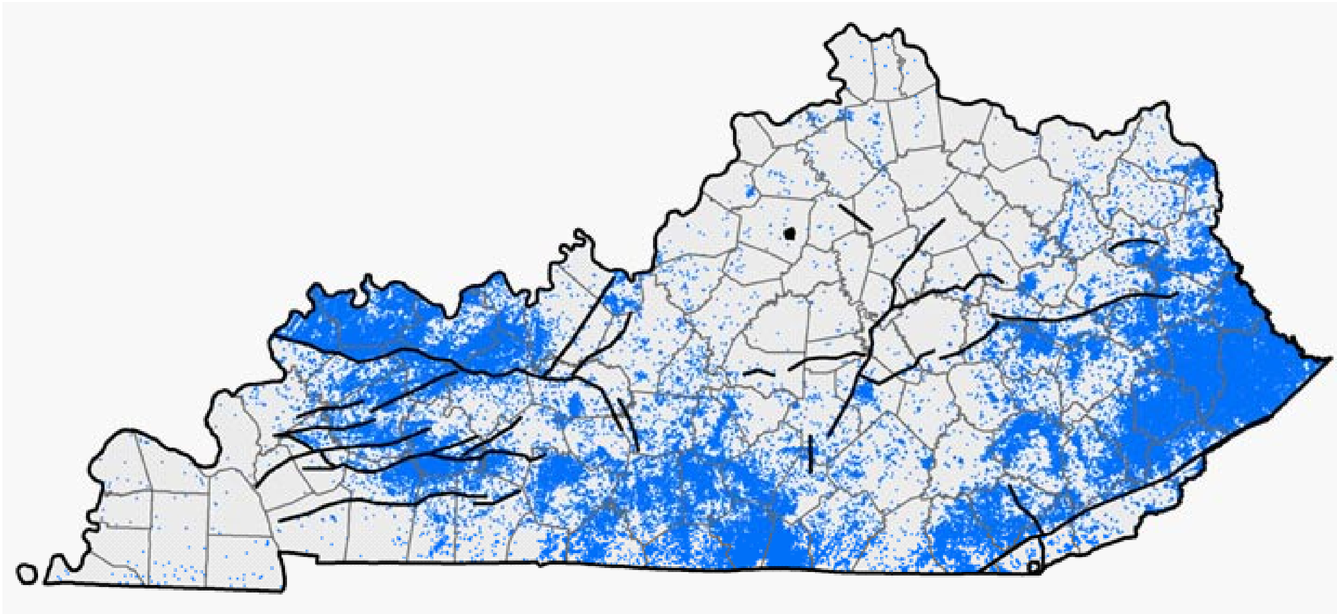

Figure A.1. Oil and gas wells in the Kentucky Geological Survey's Oil and Gas Database. Solid black lines represent major faults at the surface.

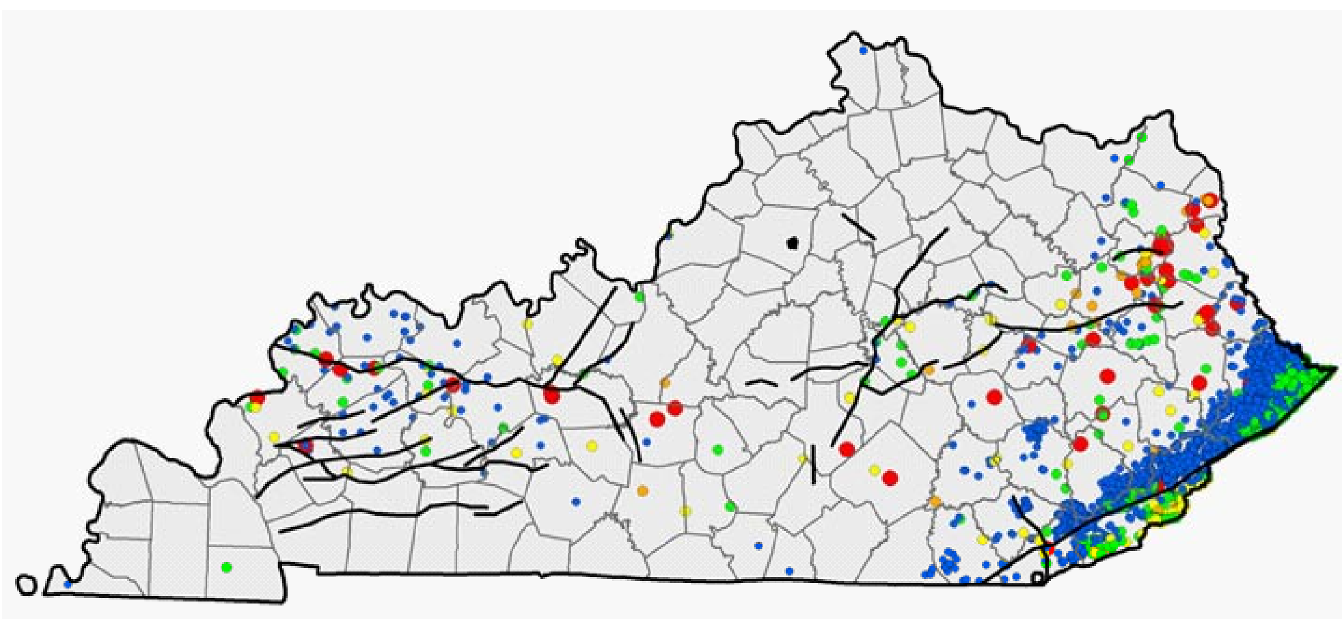

Figure A.2. Locations of wells more than 4,000 ft deep. Blue = 4,000 to 5,000 ft. Green = 5,000 to 6,000 ft. Yellow = 6,000 to 7,000 ft. Orange = 7,000 to 8,000 ft. Red = more than 8,000 ft. Solid black lines represent major faults at the surface.

tures such as folds or faults. Confirming the absence of faults in potential reservoirs and confining intervals that could act as pathways for vertical migration of injected CO_2 will likely be important for obtaining EPA permits for underground injection. Prior to and after injection, high-resolution seismic data have also been used to image and therefore document the fate of a CO_2 plume in the reservoir (White and others, 2002; Arts and others, 2004; National Energy Technology Laboratory, 2008).

Seismic data map

To help with planning for future sequestration projects, the Kentucky Geological Survey compiled a map (Plate A.1) of the locations of available seismic data in the state. Most of these seismic data is privately held, and available for sale. The map was compiled to provide users with a quick visual reference that will allow them to determine the particular areas of the state that have seismic data and the data owner or primary source for the specific data. All other information concerning the seismic data are within the purview of and available from the data owners, primary providers, or vendors, as the case may be.

Subsurface Pressure Data

The chief source of downhole pressure data is oil and gas well records. Logs in the immediate vicinity of any test site, or at the proposed horizon of injection should be checked to determine if any pressure data are included. In the absence of measured data, the hydrostatic gradient can be used to estimate a downhole pressure (Frailey and others, 2005; Wickstrom and others, 2005). The formula is:

$$\text{hydrostatic gradient minimum} = 0.433 \text{ psi/ft} = 9.795 \text{ kPa/m}.$$

Relative to downhole pressure and injection, it is also important to know the fracture gradient, or maximum hydrostatic gradient. This is the pressure that should not be exceeded in a subsurface reservoir, because it is the pressure at which the rock breaks or fractures, potentially resulting in leakage of injected gases or fluids. The EPA doesn't have a specific maximum injection pressure for Class I industrial waste injection, Class II oil and gas injection, or Class V experimental injection wells. However, the regulations state that the injection pressure cannot fracture the confining zone directly above the injection zone. Step-rate tests are usually used to calculate site-specific maximum injection pressures. In Indiana and Illinois (states with primacy), the maximum allowable injection pressure in injection wells is 0.8 psi/ft. A slightly more conservative value, 0.75 psi/ft, is sometimes applied in Kentucky:

$$\text{fracture gradient minimum} = 0.75 \text{ psi/ft} = 16.966 \text{ kPa/m}.$$

Subsurface Temperature Data

The chief source of downhole temperature data is oil and gas well records. Well logs in the immediate vicinity of any test site, or at the proposed horizon of injection, should be checked to determine if any temperature data are included. Unfortunately, downhole temperature is not a standard measurement in most wells. In the absence of measured data, the average geothermal gradient can be used to estimate a downhole temperature (Frailey and others, 2005; Wickstrom and others, 2005). The formula is:

$$\text{geothermal gradient} = 0.015°\text{F/ft} = 0.027°\text{C/m}.$$

When calculating downhole temperature, it is important to remember to start with the surface temperature and add the gradient. In Kentucky, the average surface temperature is approximately 55°F.

Subsurface Salinity Data

The chief source of downhole salinity data is water samples collected from oil and gas wells. Wells in the immediate vicinity of any test site, or at the proposed horizon of injection, should be checked to determine if samples were collected and analyzed. Unfortunately, sampling of deep wells for water has been fairly rare in Kentucky. Water salinity can also be estimated using the spontaneous-potential and/or formation-resistivity logs (see Schlumberger, 1997, charts SP-1 and Gen-9). Salinity and geochemical data for Kentucky are summarized in chapter 3 of this report.

Near-Surface Freshwater Data

An important aspect of future CO_2 injection projects will be protection of the freshwater (groundwater) zone from potential leakage. Wells will have to be cased through freshwater-bearing strata, and a satisfactory number of sealing strata will need to separate the potable water zones from the zone in which injection occurs. Current Class V experimental well permits being obtained from EPA for test injections of CO_2 are requiring monitoring of all wells and springs within a 1- to 2-mi radius of the test well. In some cases, extra monitoring wells may need to be drilled and sampled to ensure that potable water zones are not being influenced by the injected CO_2.

Static water well data are available through the Kentucky Geological Survey's Groundwater Data Repository (kgsweb.uky.edu/DataSearching/watersearch.asp). A tutorial explains how to compile available depths to groundwater in an area. KGS also provides online county groundwater resource reports for the entire state (www.uky.edu/KGS/water/library/webintro.htm). Each report is a compilation of information on the hydrology, geology, topography, and water supply and quality of the county, based on data collected from 1940 to 2000. These reports are digital updates of the USGS hydrologic atlases that cover multicounty regions. The hydrologic atlases for Kentucky have been scanned and are available online at www.uky.edu/KGS/water/library/USGSHA.html.

In general, the depth to groundwater in Kentucky is less than 300 ft; many areas have groundwater at less than 50 ft from the surface. The fresh–saline water interface is generally less than 1,000 ft beneath the surface and in many parts of Kentucky is only hundreds of feet beneath the surface (Hopkins, 1966).

Bedrock Geology

Permitting a CO_2 test well or large-scale injection project will require information on the bedrock geology of the well site and potential area of influence. Kentucky is fortunate to have detailed maps of bedrock geology at a scale of 1:24,000, which is the same scale as standard topographic maps. The geologic quadrangle maps each illustrate an area of 7.5 minutes of latitude and longitude, or approximately 7 X 10 mi. The geologic quadrangle maps are available in hard copy and as digital files online at the Kentucky Geological Survey GIS and Maps page, www.uky.edu/KGS/gis/. Each map illustrates the bedrock geology at the surface and near surface, and includes rock-unit descriptions, thicknesses, structural dips, known fault locations, and information about the economic geology of the area when it was mapped. Kentucky is one of only two states mapped at 1:24,000 scale, and the only state to provide those maps in digital form online.

KGS offers an online map service that allows users to create custom geologic maps and add data from various themes that relate to geology, land use, environmental protection, and economic development (kgsmap.uky.edu/website/KGSGeology/viewer.asp).

Seismic Hazard Data

Another type of geologic data that may be required for future carbon storage projects is seismic risk potential. The FutureGen RFP (request for proposals) required that proposed sites have peak ground acceleration of less than 30 percent g. This is a measurement of the relative strength of seismic shaking relative to the force of gravity. This limitation was for building a large energy plant with geologic sequestration, so geologic sequestration by itself may not have these guidelines. Estimates of peak ground acceleration in Kentucky can be found at the U.S. Geological Survey's Web site at earthquake.usgs.gov/research/hazmaps/.

In western Kentucky, a 30 percent g peak acceleration with a 2 percent chance of being exceeded in 50 yr is surpassed in counties west of a line from eastern Henderson to central Christian Counties (Fig. A.3). These counties are positioned within the New Madrid Seismic Zone. These estimates of peak ground acceleration are being reexamined, and this work suggests that magnitudes and peak exceedance might be overestimated (Olson and others 2005; Wang and others, 2007).

Public forums on carbon sequestration during phase I and phase II DOE-sponsored projects have shown that there is considerable public concern about the fate of injected CO_2 during an earthquake. Consequently, most phase II demonstration projects are located away from areas of potential seismic hazard to help alleviate those concerns. Because of public perceptions about the risk of an earthquake in the New Madrid Seismic Zone, there may be more concerns in western Kentucky than in other parts of the state. Aside from locating projects away from areas of known earthquakes, additional public confidence can be attained by noting the long history of drilling and injecting gases and fluids in seismic areas without harm to the public. Available technology and engineering have been designed for injection projects to prevent catastrophic releases of gases or fluids in the event of an earthquake (MRCSP, 2008).

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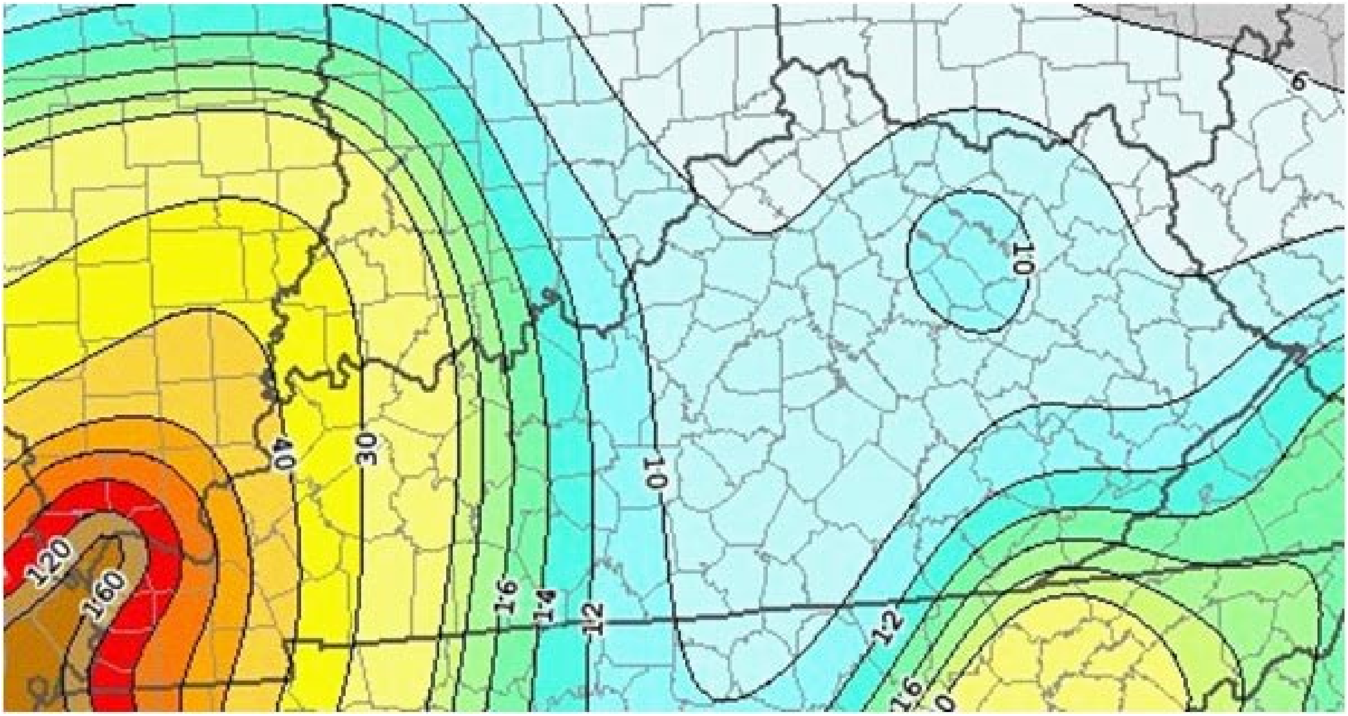

Figure A.3. Estimated peak horizontal acceleration (percent g) with 10 percent probability of being exceeded in 50 yr. From the U.S. Geological Survey National Seismic Hazards Map Viewer, gldims.cr.usgs.gov/nshmp2008/viewer.htm.

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Appendix B: Glossary

This glossary contains simplified definitions of geologic and technical terms and acronyms used in this report. Most words are defined relative to their use in carbon storage research. A good source for definitions for geological terms is J.A. Jackson's "Glossary of Geology" (1997). Good online resources include the University of California at Berkeley's geology glossary (www.ucmp.berkeley.edu/glossary/gloss2geol.html) and Cengage Learning's Geolink glossary at (college.cengage.com/geology/resources/geologylink/glossary.html). The source for most of the oil and gas field definitions is the Schlumberger oil field glossary (www.glossary.oilfield.slb.com).

Acidize. A common method of well treatment or well stimulation where hydrochloric acid is pumped under pressure into a specific rock reservoir composed of carbonate rocks or having carbonate cement, in order to increase the permeability of the reservoir near the wellbore and increase the flow of fluids or gases out of the reservoir into the well. The acidizing treatment is sometimes referred to as an *acid job.*

Adsorption. The adhesion of liquid or gas molecules onto a solid surface. For example, CO_2 molecules will adsorb onto carbon-rich surfaces, such as are found in coal or carbon-rich black shales. *Adj. Adsorptive.*

Anion. An ion with a negative charge.

Anticline. A geologic structure in which rock units are folded in a convex-upward configuration, such that the elevation of a rock unit along the axis of the fold is greater than the elevation of the rock unit on either flank. These structures are smaller scale than regional arches. The opposite type of structure is a *syncline.*

Aquifer (general). An underground layer of permeable rock or sediment that can yield significant quantities of water to a well or spring. Water generally is held in the pore spaces between mineral grains of the rock or sediment. Freshwater aquifers occur near the surface at relatively shallow depths and must, by law, be protected from contamination. *Saline reservoirs* are saltwater (brine)-bearing rock units that occur at depth and are potential carbon storage reservoirs.

Arch. A regional geologic structure in which rock units are folded upward, such that the elevation of a rock unit along the axis of the arch is greater than the elevation of the rock unit on either flank. Arches are similar to, but are typically larger scale than, anticlines. Arches may separate basins.

Argillaceous. Adjective used to describe rock or sediment that contains significant amounts of clay-size particles (shaly). Very fine-grained particles can clog pore spaces and decrease permeability in reservoirs.

Arkose. A type of sandstone containing at least 25 percent feldspar. It is typically pink or red and usually derived from rapid weathering of granitic rocks. In fact, sample cuttings from deep Cambrian arkoses have been misidentified as granites in some wells. Arkoses are typical of Precambrian and lowest Cambrian sediments in Kentucky. The relatively high potassium content in arkoses causes higher than normal gamma readings on subsurface geophysical logs, which can be misinterpreted as shaly zones. *Adj. Arkosic*

Basalt. A dark-colored (mafic) igneous (intrusive or extrusive) rock formed from lava. Basalts are a possible carbon storage reservoir where they have porosity. Carbon could theoretically be stored through mineral trapping in basalts. Basalts occur at depth in the Precambrian Middle Run Formation in Kentucky.

Basement. General term for Precambrian rocks in the subsurface. The term is informally used to differentiate dominantly igneous and metamorphic rocks of the Precambrian from the layered sedimentary rocks above. In some parts of Kentucky, the basement also contains thick Precambrian sedimentary rocks. The term "crystalline basement" may be used for Precambrian igneous and metamorphic rocks to aid in differentiating them from Precambrian sedimentary rocks.

Basement fault. A fault that extends into the Precambrian (basement) rocks. Sometimes referred to as faults "rooted in basement."

Basin. A structurally low or depressed area in the earth's crust in which thick sequences of sedimentary rock accumulated. Typically, they are large regional areas that had or have persistent subsidence for periods of geologic time.

Below drainage. Term used to define depth below the lowest level of a stream in an area. In hilly or mountainous terrain it is often important to designate depth below the lowest drainage, rather than depth below the surface, since wells drilled at the top of hills or mountains may be well above the lowest surface drainage to the side of the hill or mountain.

Bentonite. A clay layer composed chiefly of the clay mineral montmorillonite (smectite), which is usually derived from altered volcanic ash. Because smectites swell in water, bentonite layers can form confining beds that prevent vertical migration of liquids. Bentonite is commercially used as a drilling mud.

Bioturbation. Features in rocks or sediment that indicate the sediment was disturbed or inhabited by organisms, including churning, burrows, tracks, and trails. Some types of burrows are indicative of the original depositional environment of the rock. This feature is more common in marine than nonmarine rocks. Burrows commonly have different fills than surrounding rock, which can influence porosity and permeability. *Adj. Bioturbated.*

Brecciated. In geology, a rock fabric consisting of angular or broken rock fragments in a matrix or cement. The rock is called a *breccia*.

Brine. Formation water that has salinity significantly greater than seawater (35,000 mg/L TDS).

Calcite. A common rock-forming mineral composed of calcium carbonate ($CaCO_3$). Calcite is common in carbonate rocks but can occur in other rocks as well.

Carbon dioxide (CO_2). A molecule consisting of one carbon atom covalently bonded to two oxygen atoms. At earth surface temperatures and pressures it exists as a gas and it comprises about 0.04 percent of atmospheric gas. It is one of the main greenhouse gases, and its atmospheric concentration has risen coincident with the industrial revolution. Carbon dioxide is nontoxic and an important part of the global carbon cycle, in which it is produced by a large number of natural and man-made sources. Man-made sources include combustion of hydrocarbons for electricity and transportation fuel, cement manufacturing, and ethanol production.

Carbon sequestration, carbon storage. A technology or process that captures carbon dioxide from man-made emissions or the atmosphere and stores them in the biosphere (plants and animals), lithosphere (earth), or hydrosphere (ocean sequestration). Terrestrial carbon sequestration uses properties of the soil and plants to remove or store carbon dioxide. Geologic carbon sequestration involves the injection of carbon dioxide into subsurface rock units such as unmineable coals, depleted oil and gas reservoirs, carbon-rich shales, or saline reservoirs.

Carbonate. General term for rocks composed of rocks rich in carbonate (CO_3^{2-}) such as limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$), and sometimes rocks cemented by calcite. Carbonate rocks are generally more reactive to CO_2-saturated brine than noncarbonate rocks.

Carbonic acid. A weak acid formed by the dissolution of CO_2 in water. Carbonic acid is formed by the reaction $CO_2 + H_2O = H_2CO_3$.

Casing (case the well). Pipe that is lowered into a wellbore and cemented in place. Casing is placed in wells in order to isolate parts of the wellbore from surrounding rocks and fluids. In most wells, it is required through at least the intervals of fresh water in order to protect any freshwater aquifers from drilling fluids or gases. Casing may also be used deeper downhole to isolate other rock units as needed, stabilize the wellbore, or to control pressure and fluid flow. Putting casing in the ground is called “running pipe” or “casing the well.”

Cation. An ion with a positive charge.

CBM. *See coalbed methane.*

Cement (rock). Natural mineral binding material that welds framework grains together in a rock. There may be several types of cement in a sedimentary rock.

Cement (well). Material used during drilling to bind casing to the wellbore.

Cement bond log. A type of geophysical well log that uses acoustic measurements to graphically image the cement used to hold the wellbore casing in place in a drillhole. The purpose of the log is to analyze the cement for holes that would diminish the ability of the cement to prevent fluid movement between the casing and borehole wall. The annulus between the rock wall of the borehole and the casing installed in a well.

Chert. A hard, microcrystalline quartz-rick rock. Chert is harder to drill through than many other rock types, so rocks with abundant chert may require longer to drill through or cause well deviations.

Chlorite. A silicate (phyllosilicate) mineral group associated with low- to medium-temperature metamorphic rocks or hydrothermal deposits. An iron-aluminum-magnesium-silicate hydroxide mineral.

Clean (sandstone). Adjective used by drillers to describe a relatively pure or homogeneous sandstone, typically quartz-rich or quartzose in contrast to a sandstone composed of many different kinds of grains, which appears speckled or "dirty."

Closure. *See structural closure*.

Coalbed methane (CBM). Natural gas (methane) held within and produced from coal beds. Carbon dioxide might be used to enhance coalbed-methane recovery. Because the coals are carbon-rich, the carbon dioxide should be adsorbed (stick) onto the coal matrix.

Completion (well completion, complete a well). Finishing a well so it is ready to produce oil or gas. This usually involves installing production casing and cement, perforating the casing into the producing interval, treating the producing interval, running production tubing, and installing pumps, etc., for production. When examining well records, a completion indicates that there were sufficient hydrocarbons (and presumably porosity and permeability in the host reservoir) to go to the expense of installing tubing, etc.

Condensate. Volatile hydrocarbons often co-produced with natural gas that are liquid at surface temperature and pressure conditions: "wet gas." These generally are high-gravity oils.

Conductivity. A measurement used to approximate the salinity of a formation water sample. In general, as the number of ions in a formation water increases, the conductivity increases. Measured in Siemens or milliSiemens, conductivity is the reciprocal of resistivity.

Confining interval (zone). An impermeable rock interval or zone that does not allow vertical migration of fluids or gas from underlying reservoirs. Adequate confining intervals must be demonstrated to regulatory agencies for permitting an underground injection well. There may be multiple confining intervals above injection reservoirs. Also known as a *caprock* or *seal.*

Core. A cylindrical section (sample) of rock removed through drilling with a special bit and drill rig. *Full (whole or conventional) core* is cut at near the diameter of the wellbore (generally 3 to 5 in.) during drilling and is recovered in vertical sections, usually in 30-ft increments. *Sidewall cores* are much smaller cores (generally 1-in. diameter and several inches in length) drilled horizontally from the wellbore after a well has been drilled. Cores provide actual samples of rock strata for reservoir testing and analysis.

Crop out. Exposed at the surface.

Crystalline rock, crystalline basement. Metamorphic or igneous rocks, generally in deep Precambrian strata. In much of the Midwest, crystalline rocks form the bottom (basement) on which younger sedimentary rocks were deposited. The overlying sedimentary rocks contain reservoirs for oil, gas, water, and possibly carbon sequestration.

Cuttings. Fragments and chips of rocks that are cut from the wellbore by drilling. The chips are brought up the hole to the surface as part of normal drilling operations, are screened from the drilling mud, and then described by drilling personnel. Descriptions may include information about their apparent composition, color, texture, hydrocarbon content (if any), and depth. Cuttings are bagged and saved for some wells. The Kentucky Geological Survey Well Sample and Core Library has a large inventory of cutting samples from many of the deep wells in Kentucky.

Darcy. Standard measure of permeability that is equal to the passage of 1 cm^3 of fluid of 1 centipoise viscosity flowing in 1 sec under a pressure differential of 1 atmosphere through a porous medium having a cross-section area of 1 cm^2 and length of 1 cm (see millidarcy).

Density log. A type of geophysical well log that shows a graphic representation of the bulk density of rocks and their contained fluids in close proximity to the wellbore. Density measurements are taken by a wireline tool that is lowered down the well. Porosity can be calculated based on a mass-balance relationship between bulk density and porosity.

Detrital. Grains that have been eroded from other rocks or organic material.

Diagenesis. The sum of all of the biological, chemical, and physical alteration of sediment after its burial, and as it turns to stone (lithification), but not including weathering and erosion when the rock is reexposed at the surface.

Dissolution. A type of chemical weathering in which water or acidic waters dissolve parts of minerals or rocks from the surrounding bedrock. Most common in carbonate rocks.

DOE. U.S. Department of Energy. This federal organization oversees carbon capture and sequestration research in the United States.

Dolomite. A sedimentary rock dominated by the mineral dolomite, which is a magnesium-rich, rather than calcium-rich, carbonate rock. In some cases, the term *dolostone* is used to differentiate the sedimentary rock referred to as dolomite from the mineral dolomite. *Adj. Dolomitic.*

Dolomitization. The process by which a carbonate rock is altered to dolomite. This can occur during sedimentation or shortly after burial, as in arid shoreline (sabkha) environments, or can occur later in burial through the migration of hot, mineral-rich fluids through carbonate rocks.

Drillstem test (DST). A standard formation or reservoir test in which a subsurface interval of rock is isolated (usually by packers down the wellbore) and fluid is allowed to flow from the formation into the drillstem and pressures are recorded over time. A variety of pressure responses can be tested by opening and closing valves that allow fluids to flow into the drillstem.

Enhanced gas recovery (EGR). The stage of gas recovery in which a variety of methods can be used to displace residual natural gas in a reservoir so it can be more easily extracted.

Enhanced oil recovery (EOR). The third stage of oil recovery, in which a variety of methods can be used to alter the chemical or physical properties of the remaining oil in a reservoir so it can be more easily extracted. EOR typically involves injecting fluids or gases into a reservoir or heating the reservoir in order to lower the viscosity (stickiness) of the remaining trapped oil. Differs from *secondary recovery,* where the goal is repressurization or pressure stabilization in the reservoir with the simple intent to displace additional oil. Miscible CO_2 could be injected into old oil reservoirs in order to lower the viscosity of stubborn trapped oil, allowing it to flow to a producing well.

EPA. U.S. Environmental Protection Agency. The EPA has primacy over underground injection in Kentucky. Any underground injection control permit (typically referred to as a UIC permit) must be approved by EPA Region IV offices in Atlanta, Ga.

Equation of state. Functions that describe the values of pressure (P), temperature (T), and volume (V) for phases (gas, liquid, solid, or some combination) at equilibrium; that is, no net change in the properties or composition of the system without an external influence.

Facies. The recurrent and persistent assemblage of rock type, fossils, and thickness that characterize strata of a specific origin. Facies are typically used to describe parts of sedimentary rock bodies. A rock *formation* will generally consist of several different facies. Each facies may have its own porosity and permeability characteristics.

Fault. A crack in the earth's crust across which movement has occurred. The fault is a geometric plane between two rock masses. See *normal, reverse, strike-slip*, and *thrust* fault for different types of faults defined by the relative movement of rock masses on either side of the fault. *Sealing* and *transmissive* faults refer to their ability to transmit fluids or gases. In carbon storage research it is very important to identify any fault within the area of potential injection.

Feldspar. A group of common rock-forming minerals composed of aluminum and silica (aluminosilicates) with potassium, sodium, and calcium. *Adj. Feldspathic.*

Feldspathic. Adjective used to describe a rock containing abundant feldspar grains.

Felsic. Adjective used to describe the light-colored, silica and aluminum minerals in igneous rocks.

FDC (compensated formation density) log. A type of geophysical well log that shows a graphic representation of the bulk density of rocks and their contained fluids along the sides of the wellbore, which has been corrected (compensated) for fluctuations in the diameter of the borehole and the influence of drilling fluids and mud cake downhole. Density measurements are taken by a wireline tool that is lowered down the well. Porosity can be calculated based on a mass-balance relationship between bulk density and porosity.

Formation (rock unit). The basic rock unit used for mapping in geology. Formations have distinctive upper and lower boundaries and must be mappable for large distances. Formations may be composed of smaller units termed *members* and *beds.* Multiple formations may be combined into larger units called groups.

Formation water. Water present in the porosity of subsurface reservoirs or other types of buried rocks—typically sedimentary.

Frac, fracing, fracking. *See hydraulic fracture.*

Fracture (frac) pressure. The pressure at which a unit of rock fractures. This pressure must be calculated and tested for any injection well in order to determine the limits of injection pressure that will be allowed so that overlying confining intervals are not fractured.

Fracture gradient. The pressure at which a rock formation will fracture at different depths in the subsurface, typically noted as pressure per unit depth (for example, psi/ft=pounds per square inch per foot).

Framework grains. The grains that are the principal supporting structure in sedimentary rocks. Framework grains may consist of a single mineral (e.g., quartz grains), rock fragments, or fossil grains. The intervening space between the framework grains—the pore space—can be entirely or partly filled with cement or matrix.

Friable (sandstone). Adjective used to describe a rock that is poorly cemented and easily broken or crumbled.

Fugacity. Describes the effective concentration of gases under nonideal conditions (that is, high pressure), in which molecules react more strongly with other molecules.

FutureGen. A federal- and industry-sponsored project to construct the first near-zero-emissions power plant. The plant would use geologic carbon sequestration as part of a strategy to mitigate carbon emissions.

Gamma-ray log. A type of geophysical well log that shows a graphical representation of natural gamma-ray emissions from subsurface rock units. Measurements are taken by a wireline tool lowered down a wellbore. Useful for identifying shales because shales emit more gamma rays than other common rock units.

Gas-drive reservoirs. Reservoirs in which the primary recovery mechanism is dissolved and frees natural gas in the reservoir. Expansion of the gas is used to drive the oil from the reservoir into the wellbore.

Geophysics. The study of the physics of the earth, primarily through seismic, gravitational, magnetic, radioactive, or electrical means. In geology, geophysics refers to a wide array of techniques used to directly or passively gather information from beneath the surface of the earth. *Adj. Geophysical.*

Geophysical well log (well log). General term for a recording or measurement of subsurface rock and fluid properties gathered from a wireline tool lowered down a wellbore using geophysical techniques, such as measurements of spontaneous potential and resistivity (electric logs), or gamma ray and density (radioactivity), etc.

Geothermal gradient. The rate of increase of temperature in the earth with depth. The gradient varies by region, but the overall average gradient for the crust is 25°C per kilometer of depth.

Gigatonne. Metric unit equal to 1 billion metric tonnes or 1.103 billion U.S. tons (standard short tons).

Standard international unit used for measuring carbon dioxide emissions.

Glauconite. A green silicate mineral found in sedimentary rocks and consisting mostly of silica, potassium, and iron. Generally, characteristic of sediments deposited in deeper marine conditions at slow depositional rates. The high potassium content of this clay mineral can cause false porosity readings on neutron logs and high gamma readings.

Graben. A relatively downdropped block bounded by normal faults.

Granite. An intrusive igneous rock formed from magma and consisting of quartz (silica), feldspars, amphiboles, pyroxenes, and micas. In Kentucky, granites are known from subsurface Precambrian strata.

Gravity data/surveys/analyses/anomaly. Measurements of spatial variations in the earth's gravitational field. Measurements at different locations can be used to detect different densities of rock strata in the subsurface. Gravity *surveys* or *analyses* are done to map variations in the gravitational field. When mapped, *gravity anomalies* (rapid lateral changes in gravity measurements) may indicate changes in geology related to major faults or igneous intrusions.

Greenhouse effect. Heating (rising temperature) caused by greenhouse gases in the atmosphere that absorb and emit infrared radiation (heat).

Greenhouse gases. Gases in the earth's atmosphere that absorb and emit radiation from the thermal infrared range, including water, carbon dioxide, methane, nitrous oxide, and ozone. Although water is the most abundant greenhouse gas in the atmosphere, science indicates that small changes in the amount of carbon dioxide and methane (common in industrial and fossil-fuel-powered electrical-plant emissions) can cause increases in the earth's surface temperature, termed global warming, or global climate change.

Group (rock unit). A rock unit generally composed of two or more genetically related formations. This unit is designated when the formations in the group are more similar to or distinctive from each other than formations above or below the group.

Hematite. A red or silver iron-oxide mineral. *Adj. Hematitic.*

Heterogeneous. Adjective indicating variable characteristics. In sedimentary geology, heterogeneous usually denotes lateral variability in thickness, grain size, and bedding. The opposite is homogeneous. *Noun. Heterogeneity.*

Homogeneous. Adjective indicating relatively uniform characteristics. The opposite is heterogeneous. *Noun. Homogeneity.*

Horst. A relatively uplifted (positive) fault block bounded by normal faults. Horsts often bound grabens.

Huff-and-puff. In petroleum geology and carbon sequestration, an enhanced oil recovery method in which CO_2 is injected into an oil reservoir through a well. The well is then shut-in (closed) to let the injected CO_2 dissipate into the reservoir, potentially dissolving into the oil, the "soak" period. After some of time (determined by the bottom hole pressure) the well is opened to allow the oil to be produced. Several cycles of injection and shut-in (huff) followed by production (puff) may be used.

Hydraulic fracture. A well-stimulation method in which fluids are pumped into a reservoir at high pressure in order to overcome the natural confining pressure in the reservoir, causing a vertical fracture in the reservoir. The fracture is then filled (propped) with sand (or other material) to keep the fracture open. This method increases the hydraulic connectivity between the reservoir and the wellbore.

Hydrocarbon. An organic compound consisting of hydrogen and carbon. Typically refers to fuels such as natural gas, oil, and coal.

Hydrology. The study of water. In petroleum geology and carbon sequestration, hydrology involves the measurement and physical and chemical characterization of subsurface waters.

Hydrostatic pressure and gradient. The pressure exerted on a point overlain by a column of water at rest. The average hydrostatic gradient with depth in the earth is 100 bars/km or 0.43 lb/in.^{2}/ft.

Hydrothermal dolomite. Dolomite formed by precipitation from water hotter than the surrounding rocks (hydrothermal fluids) in the subsurface.

Hydrothermal fluids. Fluids, often mineral-rich, which are heated within the earth. These fluids can move along faults and fractures, altering the rocks through which they migrate.

IGCC (integrated gasification combined-cycle). A power-generation process that uses coal gasification to generate syngas (synthesis gas) to fuel gas turbines for electricity generation. Waste heat from the gasification and combustion processes are also captured to make steam that is then used to generate electricity from steam turbines. IGCC plants are more efficient than conventional coal-combustion plants, and result in lower levels of emissions. The gasification process produces a nearly pure stream of CO_2, which can be easily captured for storage.

Immiscible. Phases of fluids or gases that will not mix. Relative to carbon storage, immiscible conditions occur when pressures and temperatures are too low (and depths are too shallow) for CO_2 to mix with subsurface fluids (salt water, oil) or natural gas, so that any injected CO_2 would remain as a separate phase in the reservoir. Shallow, immiscible enhanced-recovery projects are expected to rely primarily on displacement of hydrocarbons in the reservoir.

Injection fall-off test. A downhole test used to measure the injectivity of a formation. During an injection fall-off test, gas or fluids are injected into a formation through tubing at a steady rate and pressure. The well is then shut-in, and the pressure of the reservoir is monitored over time with gauges. The rate at which pressure returns to pre-test conditions is a function of the permeability and volume of the reservoir.

Injectivity. In petroleum geology and carbon sequestration, a measure of a reservoir's ability to have gas or liquid injected into it.

Intercrystalline porosity. Microscopic porosity formed between crystals in rock cements. Typically formed in carbonate rocks as a result of diagenesis.

Isopach (map). A thickness map in which lines connect points of equal thickness, similarly to elevation contours on topographic maps.

Isotope. One of two or more species of the same chemical element, in which the species have the same number of protons in a nucleus but different numbers of neutrons. The ratio of isotopes for a given element, such as carbon and oxygen, is sensitive to a wide variety of chemical (e.g., mineral precipitation) and physical (e.g., evaporation) processes, and therefore the isotopes can be used to infer the processes that affected the occurrence and distribution of the element. *Adj. Isotopic.*

Kaolinite. An earthy, white to tan clay.

Karst. The terrain and features associated with dissolution of soluble bedrock, usually carbonates, that form caves, sinkholes, springs, and other features.

KGS. Kentucky Geological Survey. A research branch of the University of Kentucky, which is charged with increasing the knowledge and understanding of the mineral, energy, and water resources, geologic hazards, and geology of Kentucky for the benefit of the commonwealth and nation.

Kimberlite. Igneous, ultramafic (dark iron-magnesium minerals), intrusive rock composed of at least 35 percent olivine (a magnesium iron silicate mineral).

KYCCS. Kentucky Consortium for Carbon Storage. A State and industry partnership in Kentucky conducting research on carbon sequestration. This partnership is administered by the Kentucky Geological Survey and is separate from the U.S. Department of Energy regional carbon sequestration partnerships. KYCCS maintains a Web site at www.kyccs.org.

Laminae (laminations). The thinnest unit layer of deposition in a sedimentary rock. Laminae are less than 1 cm (0.39 in.) thick.

Limestone. A sedimentary rock consisting of more than 50 percent calcium carbonate formed from physical or chemical processes.

Litharenite (lithic arenite). A sandstone containing more than 25 percent rock (lithic) fragments and having less than 75 percent quartz grains and less than 10 percent feldspar grains.

Lithology. The description or physical character of a rock. Generally includes rock type, grain size, bedding, mineral constituents, and cements.

Mafic. Term used to describe dark, iron-magnesium minerals in igneous rocks.

Magnetic data/analyses/anomaly. Measurements of spatial variations in the earth's magnetic field. Measurements at different surface locations can be used to detect different densities of rock strata in the subsurface. Magnetic *surveys* or *analyses* are done to map variations in the magnetic field. When mapped, *magnetic anomalies* (rapid lateral changes in magnetic measurements) may indicate changes in geology related to mineral-bearing ore bodies or large oil fields.

Matrix. The ground mass or finest-grained component of a rock in which framework grains or crystals are embedded. Typically used in carbonate rocks to describe the fine-grained material that surrounds and encompasses larger particles or framework grains.

Matrix porosity. Microscopic porosity of the rock matrix, or finer-grained ground mass of a carbonate rock.

Mcf. Thousand cubic feet; a standard measure of volume in gas fields. See unit conversion table for equivalents. Mcfg/d would be thousand standard cubic feet of gas per day. In this context, MMcf indicates million standard cubic feet.

md. Millidarcy. A standard unit of permeability equal to 1/1,000 of a Darcy. *See Darcy.*

MGSC. Midwest Geological Sequestration Consortium. One of seven regional partnerships funded by the U.S. Department of Energy for carbon sequestration research. This partnership is administered through the Illinois State Geological Survey and covers the Illinois Basin, including western Kentucky. The Kentucky Geological Survey is part of the consortium.

Mica. A phyllosilicate mineral. Mica is a common constituent of sedimentary rocks, typically appearing as reflective flakes or sheets. *Adj. Micaceous.*

Micrite. Very fine-grained crystalline carbonate rock or matrix of carbonate rocks. Typically formed from carbonate muds. *Adj. Micritic*.

Mineralogy. The study of the mineral components of a rock. In carbon storage research it is important to know the minerals that compose a reservoir or confining interval because different minerals will react (or not react) with acids, fluids, and CO_2 at different pressures and temperatures.

Mineral trapping. The process in which CO_2 injected into a reservoir dissolves into the formation water (solubility trapping) and forms ionic species, such as bicarbonate, that subsequently react with cations, such as calcium, magnesium, and iron, to form carbonate minerals. Mineral trapping is considered the most permanent form of geologic storage, but it is also one of the slowest.

Miscible. Phases of fluids or gases that will mix into a homogenous mixture. Relative to carbon storage, the term is used when pressures and temperatures are high enough (and depths are great enough) for CO_2 to mix with subsurface fluids (salt water, oil) or natural gas in a reservoir.

Mol or Mole. The mass (in grams) of a substance that contains 6.023×10^{23} atoms, ions, or molecules, and which is equal to the atomic or formula weight.

Moldic porosity. Pores that result from the removal or dissolution of a grain or fossil shell that retain the "mold" or general shape and size of the original grain or shell.

MRCSP. Midwest Regional Carbon Sequestration Partnership. One of seven regional partnerships funded by the U.S. Department of Energy for carbon sequestration research. This partnership is administered through Battelle Memorial Institute and covers the mid-Atlantic, northern Appalachians, Michigan Basin, and Arches Provinces, including central and eastern Kentucky. The Kentucky Geological Survey is part of the consortium.

Mud log. A graphic representation of the rate a drill is penetrating subsurface rock units while drilling, with notes on rock type from drill cuttings, and other parameters noted during drilling.

MW (megawatt). Standard unit in the electrical-power industry equal to 1 million watts.

Neutron log (neutron porosity log). A type of geophysical well log that shows a graphic representation of the interactions of fast neutrons (or neutron and gamma rays) emitted from a downhole source with rock and pore fluids. A neutron log principal-ly measures the effect of hydrogen in pore fluids, so it indirectly measures relative porosity. Most neutron-porosity logs are calibrated for fresh water and rock types, and must be recalibrated (or recalculated) for different rock types. Typically, neutron logs are calibrated to calcite, which means they are scaled to true porosity in limestones, but have to be rescaled for other rock types.

Normal fault. A type of fault in which one side of the fault (the hanging wall) has moved down relative to the other side (footwall). The opposite is a reverse fault. Most normal faults are high-angle, or near-vertical in orientation.

Openhole, open hole. The (usually) lowermost part of the wellbore in which no protective casing or pipe has been. When used to describe production, it generally means that all intervals below a certain depth to the bottom of the well are not cased. In an injection well, an *openhole completion* would mean injection into the entire uncased interval below a certain depth to the bottom of the well.

Oolite. Carbonate rock composed of tiny, rounded, accretionary (gradually increasing in size) particles or grains. The grains are called ooliths. *Adj. Oolitic*.

Organic content. A measure of the amount of organic carbon in a material. Organic content is significant in carbon sequestration because high organic contents in some rocks can cause adsorption of carbon dioxide.

Organic rich. Used to describe a rock that contains large amounts of solid organic carbon components. Organic content is significant in carbon sequestration because high organic contents in some rocks can cause adsorption of carbon dioxide.

Packer. In drilling, a device that can be expanded downhole in the wellbore or casing to seal off intervals of the well for testing, cementing, or casing. When two packers are used to isolate a zone, they are sometimes referred to as *straddle packers.*

Paleokarst. Ancient karst. Surface or interval in rock with evidence of ancient karst, including dissolution, sinkholes, conduits, formed from ancient exposure of a carbonate surface and ancient weathering and erosion of that surface or intervals beneath that surface.

Paleotopography. Related to an ancient land surface that was buried. The term implies an uneven surface with buried hills and valleys generally along an unconformity. *Adj. Paleotopographic.*

Paleotopographic high. A structural high on a paleotopographic surface, such as an unconformity surface. A buried hill. In some cases, paleotopographic highs or lows may preferentially have porosity or permeability and trap oil, gas, or water. Areas of preferential permeability development may have carbon storage potential. A *paleotopographic low* would be a buried valley or depression.

Peak ground acceleration. A measure of the maximum acceleration (change in velocity) of a particle during the course of an earthquake motion. Essentially a measure of the maximum amount of shaking that is likely during an earthquake. The U.S. Geological Survey maps peak ground acceleration in earthquake-prone areas for earthquake hazard analysis.

Perforate, perforated interval. After production casing or tubing is placed in a wellbore, the casing is shot with holes that penetrate the casing. The holes allow oil or gas from the producing formation to enter the casing and be pumped to the surface in a production well. In an injection well, perforations allow fluid or gas to be injected into a specific rock reservoir, or specific part of a rock reservoir, from the wellbore.

Permeability. A measure of the degree to which fluids can move through a rock; in other words, the connectivity of pores and fractures. Permeability is generally measured in darcies or millidarcies (md).

Petrography. A measure within a rock unit. The study of the mineral and textural relationships of rocks using microscopy and other techniques. *Adj. Petrographic.*

pH. The measure of hydrogen ion activity in solution and is equal to the negative logarithm (base 10) of the hydrogen ion concentration. It is a measure of a solution's acidity.

Physical trapping. The process in which CO_2 as a buoyant free-phase is trapped below low-permeability seal rocks in a closed trap—called "structural and stratigraphic trapping"—or in which no closed trap exists and CO_2 slowly migrates in a saline aquifer over long distances—called "hydrodynamic trapping." In the latter case, CO_2 is eventually trapped over time by residual, structural, or mineral trapping processes.

Porosity. The ratio of the relative amount of open or void space in a rock to the total volume of the rock.

ppm. Acronym for parts per million, which is a standard unit in which concentration of ions of dissolved constituents are reported in a weight-per-weight basis as a dimensionless ratio. As a practical matter, ppm is equivalent to milligrams per liter.

Primary porosity. Porosity remaining from the original deposition of a sediment. *See also porosity and secondary porosity.*

Pseudomatrix. Term used to describe very fine-grained (pasty), interstitial, or intergranular (between grain) material, which looks like a matrix but is discontinuous or different from the matrix. Pseudomatrix typically is formed through the deformation or dissolution of weak detrital grains.

psi. Acronym for pounds per square inch, a standard unit of pressure.

Quartzarenite. A type of sandstone composed of more than 95 percent quartz grains.

Quartzose. Quartz-rich rock. For sandstones, used as a general term for a rock that is either a quartzarenite or a quartz-rich litharenite.

Reservoir. A porous and permeable rock body in the subsurface containing quantities of oil, gas, or water and generally isolated to a specific interval by surrounding less-permeable rock, forming confining layers or traps.

Residual trapping. The process in which CO_2 fills very small pore spaces between and within grains making up the rock, which renders the CO_2 immobile.

Resistivity log. A type of geophysical well log that measures the electrical resistivity of subsurface rocks and interstitial pore fluids. It is useful for delineating hydrocarbons in pore spaces of rock because water conducts electricity but oil and gas do not. Part of a standard electric log along with spontaneous potential.

Reverse fault. A type of fault in which one side of the fault (the hanging wall) has moved up relative to the other side (footwall). The opposite is a normal fault.

Rhyolite. A silica-rich, extrusive igneous rock; a felsic igneous rock. In Kentucky, rhyolites are known from subsurface Precambrian strata.

Rift. A tensional feature formed when blocks of the earth's crust pull apart. Typically forms a large graben bounded by faults.

Salinity. Equals the total amount of solids (milligrams per liter or parts per million) remaining in a water sample that is evaporated to dryness.

Saline aquifer. A subsurface reservoir containing highly saline water (typically more than 10,000 ppm of dissolved salts). In carbon sequestration research, the term is typically used to denote regionally widespread, saltwater-bearing units, compared to more local oil and gas reservoirs, which may also contain salt water, but only in small areas.

Saline water. Water that contains a significant concentration of dissolved salts. Freshwater salinity equals 1,000 ppm or less of total dissolved solids and seawater salinity averages 35,000 ppm of total dissolved solids. Brines have salinities significantly greater than seawater. For purposes of underground injection, it is critical to know the depths of fresh, potable water and the salinity of deeper waters in potential storage reservoirs.

Sandstone. A sedimentary rock composed of sand-size grains. Sand grains are often naturally cemented together. Porous and permeable sandstones are common reservoir rocks. The thickness, lateral extent, mineralogy, porosity, permeability, and homogeneity are some of the factors that influence its potential for carbon storage.

Seal. An impermeable rock layer that does not allow vertical or lateral migration of fluids or gas from underlying or adjacent reservoirs. Adequate seals must be demonstrated to regulatory agencies for permitting an underground injection well. A *confining layer.*

Sealing fault. Faults are termed sealing when fluids and gases are confined within a reservoir by the faults. Sealing faults form *structural traps* in *reservoirs*. When faults are conduits for fluid or gas migration they are termed *transmissive faults.*

SECARB. Southeast Regional Carbon Sequestration Partnership. One of seven regional partnerships funded by the U.S. Department of Energy for carbon sequestration research. This partnership is administered through the Southern States Energy Board and covers the southeastern United States, including the southeastern part of the Eastern Kentucky Coal Field.

Secondary porosity. Porosity that develops after deposition, typically through fluid migration and dissolution, fracturing, etc. *See also porosity and primary porosity.*

Secondary recovery. The second stage of oil or gas recovery. The first stage is natural flow due to gravity or pressure from the reservoir to the wellbore. When that motive force decreases, an external fluid or gas is injected into the reservoir through selected wells in order to increase or maintain pressure in the reservoir and push or displace *hydrocarbons* to a producing well. *Waterfloods* are the most common type of secondary recovery, but there are many different methods. In contrast to secondary recovery, where the goal is repressurization, *enhanced oil and gas recovery*, or *tertiary recovery,* involves methods that alter the chemical or physical composition of the residual oil or gas in the reservoir.

Sedimentary basin. A broad low area in the earth's crust in which sediments accumulated and lithified to form sedimentary rocks.

Shale. A lithified, fine-grained sedimentary mudstone composed of clay- and silt-size particles. Shales, in contrast to mudstones, have a finely laminated structure, called fissility, along which the rock breaks readily. Shales typically have low porosity and permeability, and, where thick, often form good confining intervals or natural seals.

Show of oil or gas. In drilling, an indication of oil or natural gas in a wellbore. A show is typically determined at the surface from fluorescence in cuttings when they come to the surface or increased gas readings on gas detection equipment.

Shut-in well. A well that could produce hydrocarbons (oil or natural gas) that is temporarily sealed or shut off for some economic or technical reason.

Sidewall core. A core taken from the side of a wellbore. These cores can be taken after a well has been drilled, as opposed to full (whole or conventional) core, which is taken during drilling. Sidewall cores, however, are much smaller than whole (conventional) core, generally 1 in. or less in diameter and 1 to 2 in. long. Cores provide actual samples of rock strata for reservoir testing and analyses.

Siltstone. A sedimentary rock composed of silt-size grains.

Seismic data/surveys/analyses. Measurements of elastic waves of energy (typically transmitted by P and S waves) used to interpret the composition, fluid content, and layering of rock units in the subsurface. Typically, a seismic wave is generated at a source on the surface and then a series of monitoring devices measure the reflection of the energy as it reflects off of subsurface rock units. The data are then processed to produce a seismic cross section of the subsurface rock layers. Seismic surveys have been required for all of the DOE-sponsored carbon dioxide injection test wells in order to determine if there were any faults or structures within the area of influence that could negatively influence containment of the injected carbon dioxide.

Seismic risk/hazard analysis. Method for examining the potential consequences or probabilities of earthquakes in an area. Seismic risks are determined based on past occurrences of earthquakes in an area and computer modeling of the likely manner in which bedrock and sediment will propagate seismic energy in an earthquake. Seismic-risk analysis is required for most federal building and construction projects, and may be needed for large-scale underground injection projects. The U.S. Geological Survey has published seismic-risk maps for the entire United States.

Skeletal grains. Grains in carbonate rocks formed from the calcite or aragonite skeletons of marine plants and organisms. For example, shell fragments are common skeletal grains.

Solubility. The extent to which one substance will dissolve into another. For carbon storage, the focus is on the degree to which CO_2 will dissolve into formation waters.

Solubility trapping. The process in which CO_2 dissolves into formation waters. The extent of dissolution generally decreases with increasing temperature and salinity, and increases with increasing pressure. The process removes CO_2 as a separate buoyant phase.

Solution features. Any physical feature formed from the solution of soluble rocks, such as limestone, by acidic water. Features include any of a number of karst features such as conduits, caves, sinkholes, etc.

Sorting (sandstone). Fabric of sedimentary rocks, typically applied to sandstones, which describes the general distribution of grain sizes in the rock based on standard deviations. Very well sorted means 0.35 to 0.50 standard deviations, which means that most of the grains in the rock have similar size. Poorly sorted means 1.4 to 2.0 standard deviations, which means there is a wide distribution in grain sizes. Well-sorted sandstones typically have better porosity than poorly sorted sandstones because small grains fill the poor spaces between larger grains in poorly sorted sandstones (although other factors also influence porosity).

Source rock. A rock unit with a high organic content that if heated could or has generated hydrocarbons. Hydrocarbons then migrate to reservoirs. Most source rocks are organic-rich shales, typically containing at least 1 percent organic matter and at least 0.5 percent total organic carbon. In Kentucky, for example, the Devonian black shales (Chattanooga Shale, Ohio Shale, New Albany Shale) are known source rocks.

Spontaneous potential (SP) log. A type of geophysical well log that measures the electrical potential of subsurface rocks and interstitial pore fluids from wireline tools lowered down the wellbore. This log is useful for detecting permeability in subsurface rock layers because it detects differences in salinity between drilling muds and formation fluids. It is also useful for determining clay content of beds. It is part of a standard electric log, along with resistivity.

Standard deviation. A measure of the spread of values from their average.

Stimulation. A well treatment used to restore or enhance productivity in a well, or enhance the permeability or hydraulic connectivity between the reservoir and the wellbore.

Straddle packers. *See packers.*

Stratigraphy. The study and correlation of rock units to determine their relative stacking, distribution, depositional origins, and ages. *Adj. Stratigraphic.*

Stratigraphic trap. A trap or seal on a *reservoir* in which changes in rock types, layering, or bedding form the *seal* or *trap*.

Strike-slip fault. A type of fault in which the rock blocks on either side of the fault slide past each other, rather than up or down relative to the other block. Informally termed a tear fault.

Structure. A geologic feature formed from deformation of the earth's crust, such as a fault or fold. *See also structure map. Adj. Structural.*

Structural closure. Term used to indicate a closed structural contour on a structure map, generally denoting a structural high in a reservoir, which may form a *structural trap*.

Structural relief. The relative difference in depth from the top of a surface to the base of a surface (for example, the top surface of a rock unit) at depth across some structure, *paleotopographic* feature, or trap, generally referring to an irregular *unconformity* surface or a reservoir.

Structural trap. A *trap* or *seal* on a *reservoir* in which the reservoir is sealed along a fault or through the dip or attitude of beds in a structure such as an *anticline* or *syncline*.

Structure map. A subsurface map of a surface, such as the top or bottom of a rock unit or reservoir. Contour lines on the map represent points of equal elevation, generally drawn relative to a sea-level datum, although other datums may be used. Hence, they are similar to a topographic map of a subsurface unit. Structure maps are useful for determining the dip of rock strata and the occurrence of structural features such as anticlines and synclines.

Subcrop. Point or line at the surface where a subsurface rock unit comes to the surface of bedrock. The rock unit may be covered by modern alluvium and soil, and not actually exposed or *cropping out*.

Sublitharenite. A type of sandstone between lithic arenite (litharenite) and quartzarenite. Composed of 75 to 95 percent quartz and 5 to 25 percent rock (lithic) fragments.

Subsea. Below sea level. The term is generally used to denote elevation below sea level on structure maps and cross sections.

Supercritical (fluid). Refers to a substance that exceeds its critical point (critical temperature and pressure) with near-liquid density and a viscosity similar to the gas phase. For CO_2, the critical point is 1,085 psi at 88°F (74.8 bar at 31.1°C), which occurs at depths of approximately 2,500 ft in most of Kentucky. For industrial-scale geologic sequestration, keeping CO_2 at supercritical conditions in underground reservoirs will be important, because there is a significant (approximately 250 times) volume reduction of supercritical CO_2 relative to gaseous CO_2.

Syncline. A local geologic structure in which rock units are folded (downwarped), such that the elevation of a rock unit along the axis of the structure is less than the elevation of the rock unit on either flank. These structures are smaller scale than regional basins. The opposite type of structure is an *anticline.*

Synsedimentary. Occurring when the sediment that formed the sedimentary rock was deposited.

TD. Acronym for total depth of a well.

Total dissolved solids, TDS. The total dissolved material in a liquid, measured as the materials small enough to pass through a filter or sieve of 2 micrometers. TDS measurements are used for salinity analysis. Deep formation waters are salty and have high TDS values.

Tertiary recovery. *See enhanced oil or gas recovery.*

Thrust fault. A type of reverse fault in which one fault block has moved or been thrust over or across another fault block. Typically, these are low-angle, sometimes near-horizontal, faults.

Tight (rock unit). Adjective used to describe rock units that show little permeability or are well cemented.

TOC. Acronym for total organic carbon. A common measure of the amount of organic carbon in a rock unit. It is an important measurement for determining original source rocks and for determining *adsorption* mechanisms relative to the injection of carbon dioxide in the subsurface.

Ton. Standard U.S. ton, also called a short ton, equals 2,000 U.S. pounds or 0.907 metric tonne.

Tonne. Metric ton, equals 1,000 kilograms or 1.103 U.S. short tons.

Trachyte. Igneous, extrusive volcanic rock that is fine-grained and dominated by alkali feldspar and minor mafic (dark) minerals.

Transmissive (fault). Faults are termed transmissive when fluids and gases can migrate along the faults or fractures associated with faults. Faults can also be *sealing* and form *traps*.

Trap. In oil and gas geology, a rock reservoir capable of holding hydrocarbons and sealed by relatively impermeable rocks through which the hydrocarbons will not migrate. *See also structural trap and stratigraphic trap.*

Treatment (well treatment). General term for methods in which fluids are pumped down a well to resolve a wellbore or reservoir condition. *See stimulation*.

TVD. Acronym for true vertical depth of an intentionally deviated or horizontal well from the ground surface to the deepest penetration of the wellbore in a vertical plane. The measured depth of the well is the total length of the wellbore. TVD is used with wellbore deviation data to correct observed rock unit thicknesses as penetrated at some angle to the actual bedding to the true vertical thickness of the unit.

Unconformity. A rock surface that represents a substantial gap in the geologic record in which rock units below the surface are overlain by rock units that would not be in depositional succession. Typically, it is either an erosive contact or a surface of ancient exposure and weathering. A number of terms apply to different scales of unconformity (and disconformity) related to the scale (or area) of the surface, or the relative geometry of the units above and below the surface. Oil and gas traps (and porosity development) are common beneath unconformity surfaces.

Unconsolidated. In geology, adjective applied to sediments or rocks, to indicate they are uncemented. Drillers sometimes use this as an adjective to describe poorly cemented or uncemented rocks downhole.

University of Kentucky. A large public university in Lexington, Ky., known primarily for the success of its basketball team and the Kentucky Geological Survey, one of its research centers.

Vug. A large pore or cavity in a rock. Typically an irregularly shaped pore of nonspecific origin. *Adj. Vuggy, vugular.*

Vuggy porosity. Porosity formed from vugs. It is typically larger than the grains that comprise the rock, or the crystals in the cement holding the grains together.

Water-drive reservoirs. Reservoirs in which the primary recovery mechanism is pressure from natural water in the reservoir, generally at a position below the oil or gas layer.

Waterflood. A type of secondary recovery in which water is injected into a reservoir from one or more injection wells, and used to push or displace residual oil toward a producing well.

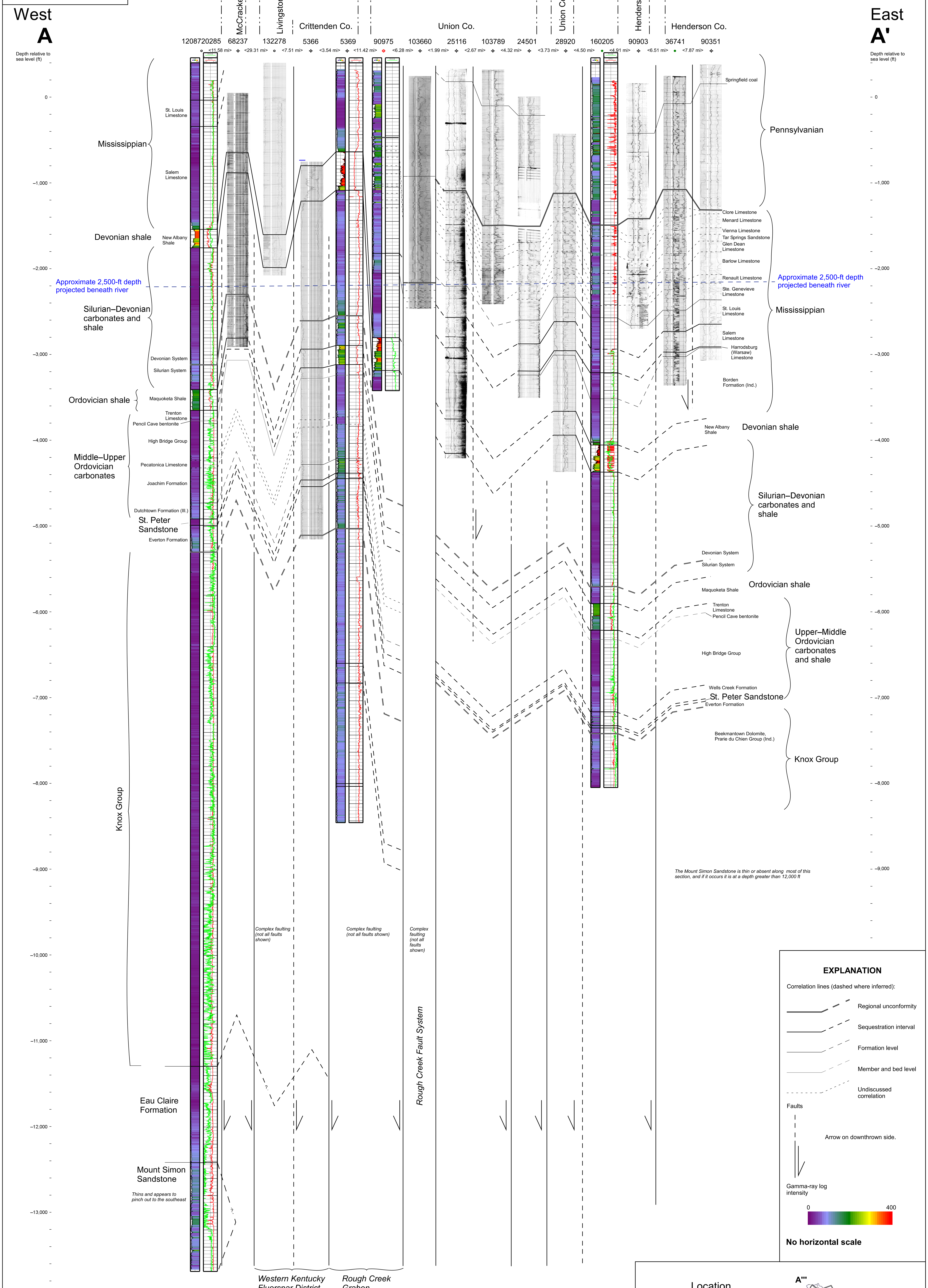
Water saturation. The fraction of water that occupies the pore space, typically expressed as a percentage.

Wellbore. A hole drilled in the ground. Pertaining to the drillhole or the rocks that line the drillhole.

Wireline (logging). A method of deploying in a wellbore retrievable tools that are suspended from an electrically conductive cable for the purpose of acquiring continuous measurements of rock and fluid properties. Nuclear logs measure radioactive properties and provide information on density, porosity, fluids, and rock type. Electrical logs measure natural and induced electrical properties and provide information on rock type, porosity, and fluids. Geophysical logs provide measurements of physical properties of rock types (sonic velocities) and porosity. Mechanical logs provide information on variations in borehole diameter, velocity of fluids in the borehole, and other properties. Often the tool as deployed contains multiple sources and sensors of each major type and all are recorded simultaneously for later analysis.

Plate 4.1.

Ohio River (west) cross section.
Chapter 4: Geologic Carbon Storage (Sequestration) Potential in Kentucky



The rock unit intervals correlated in this cross section are described in the accompanying report. Correlations represent interpretations of approximate depths and thicknesses of the units based on available data. Actual depths and thicknesses may vary, especially in faulted areas. It is also important to understand that an interval described as a potential saline reservoir will not have characteristics that allow injection and carbon storage across the entire thickness shown. Potential storage will only be possible in much smaller zones of those intervals, as discussed in the accompanying report.

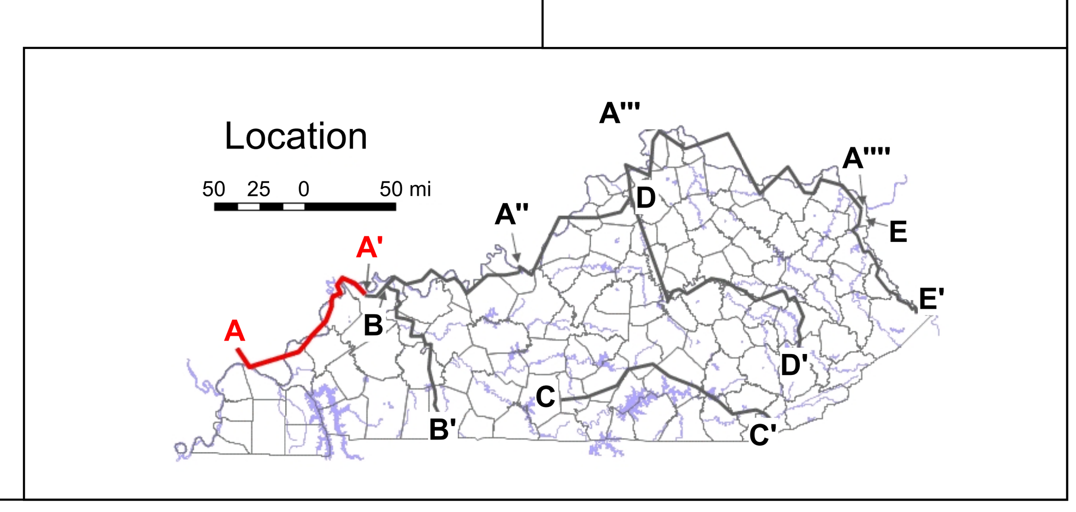
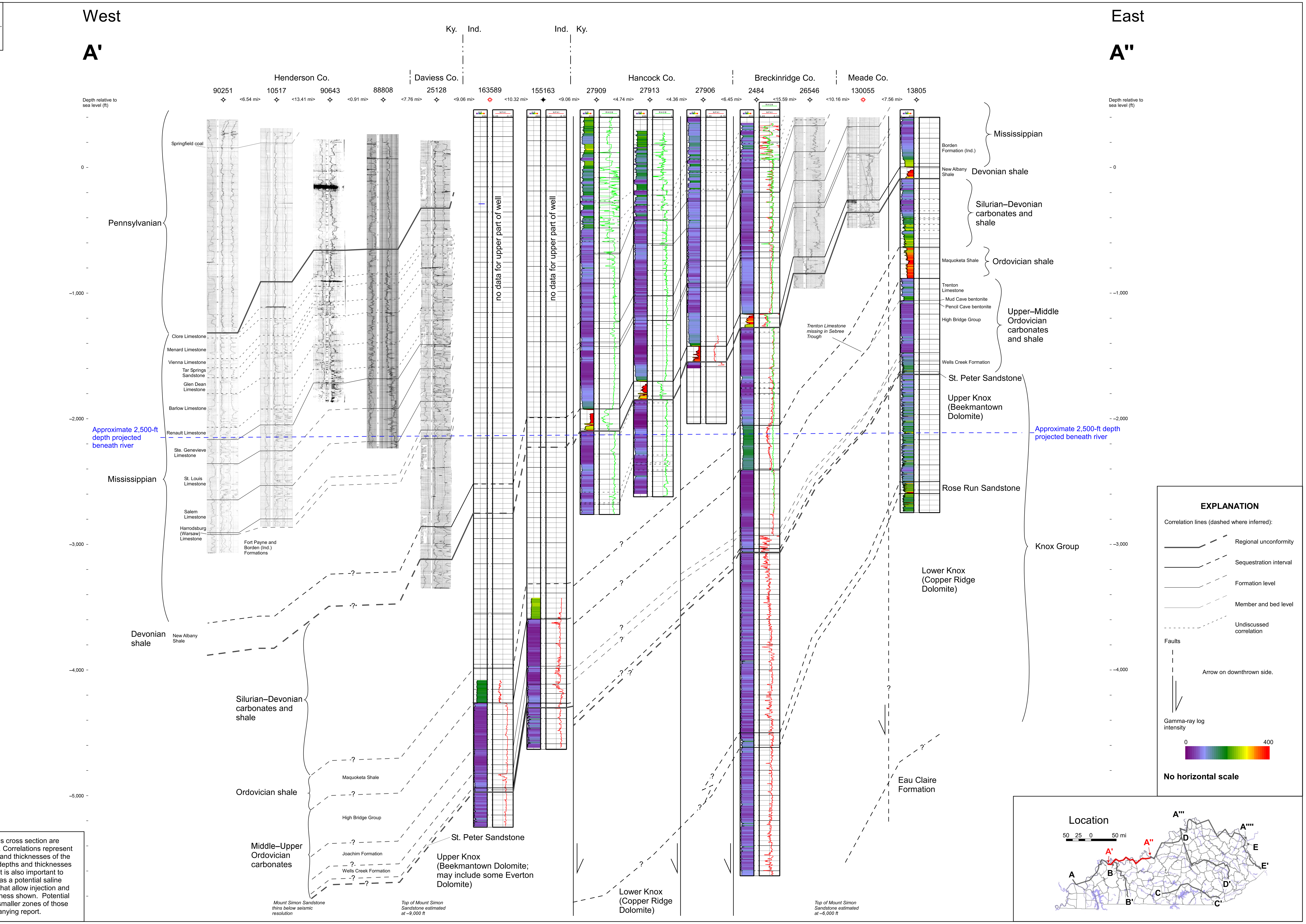
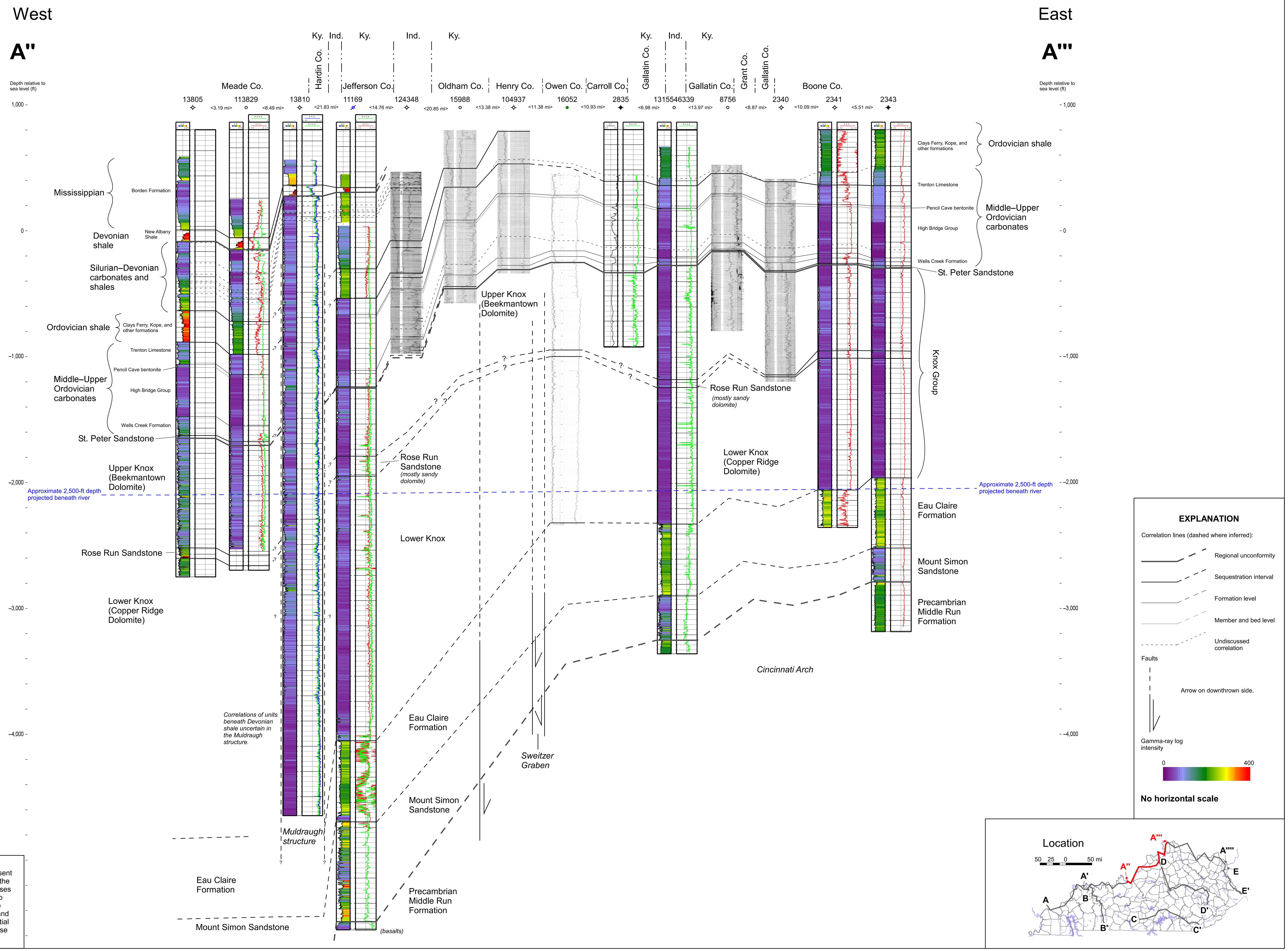


Plate 4.2.
Ohio River (west-central) cross section.
Chapter 4: Geologic Carbon Storage (Sequestration) Potential in Kentucky



The rock unit intervals correlated in this cross section are described in the accompanying report. Correlations represent interpretations of approximate depths and thicknesses of the units based on available data. Actual depths and thicknesses may vary, especially in faulted areas. It is also important to understand that an interval described as a potential saline reservoir will not have characteristics that allow injection and carbon storage across the entire thickness shown. Potential storage will only be possible in much smaller zones of those intervals, as discussed in the accompanying report.

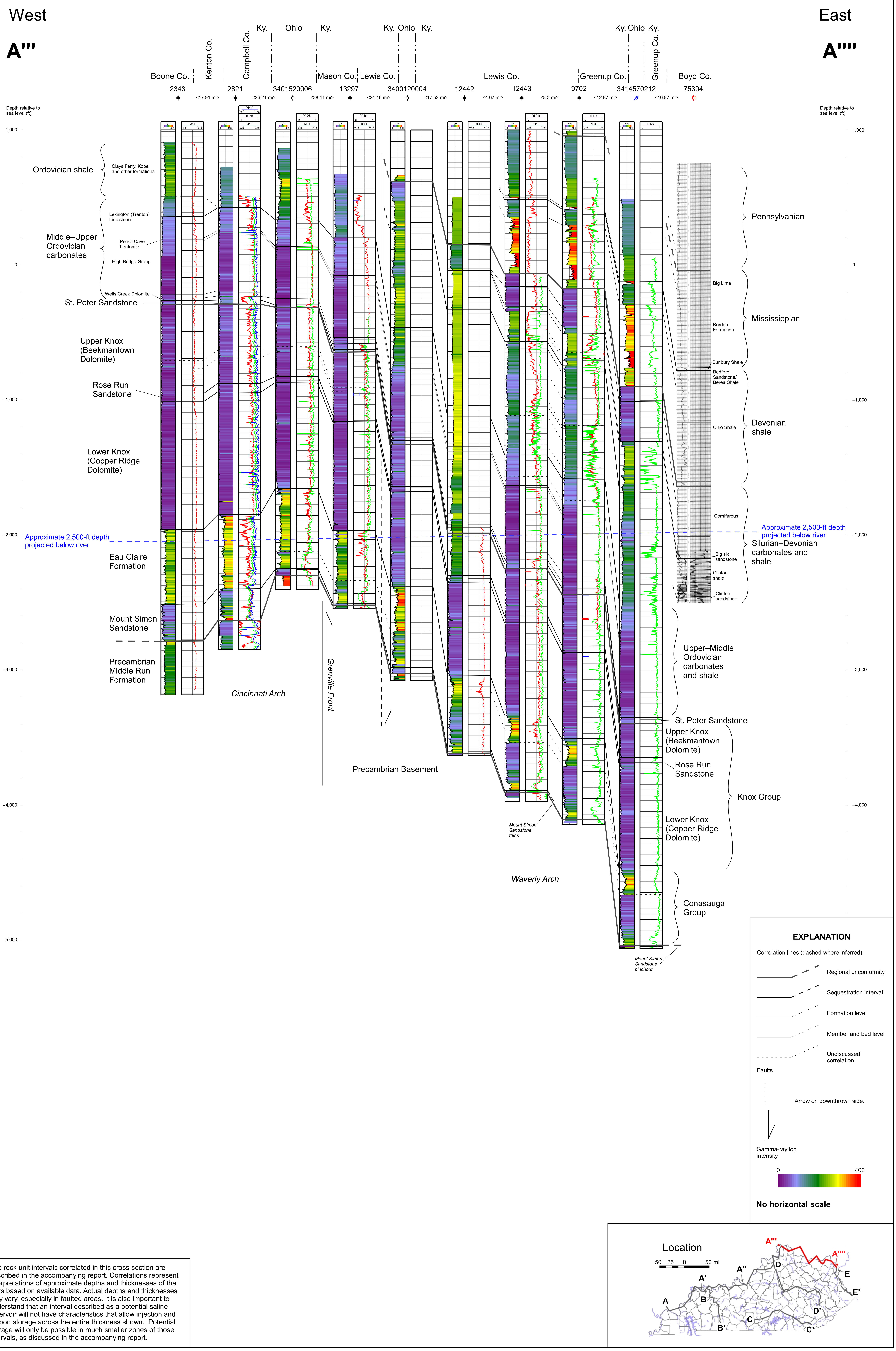
Plate 4.3.
Ohio River (east-central) cross section.
Chapter 4: Geologic Carbon Storage (Sequestration) Potential in Kentucky



The rock unit intervals correlated in this cross section are described in the accompanying report. Correlations represent interpretations of approximate depths and thicknesses of the units based on available data. Actual depths and thicknesses may vary, especially in faulted areas. It is also important to understand that an interval described as a potential saline reservoir will not have characteristics that allow injection and carbon storage across the entire thickness shown. Potential storage will only be possible in much smaller zones of those intervals, as discussed in the accompanying report.

Plate 4.4.

Ohio River (east) cross section.
Chapter 4: Geologic Carbon Storage (Sequestration) Potential in Kentucky



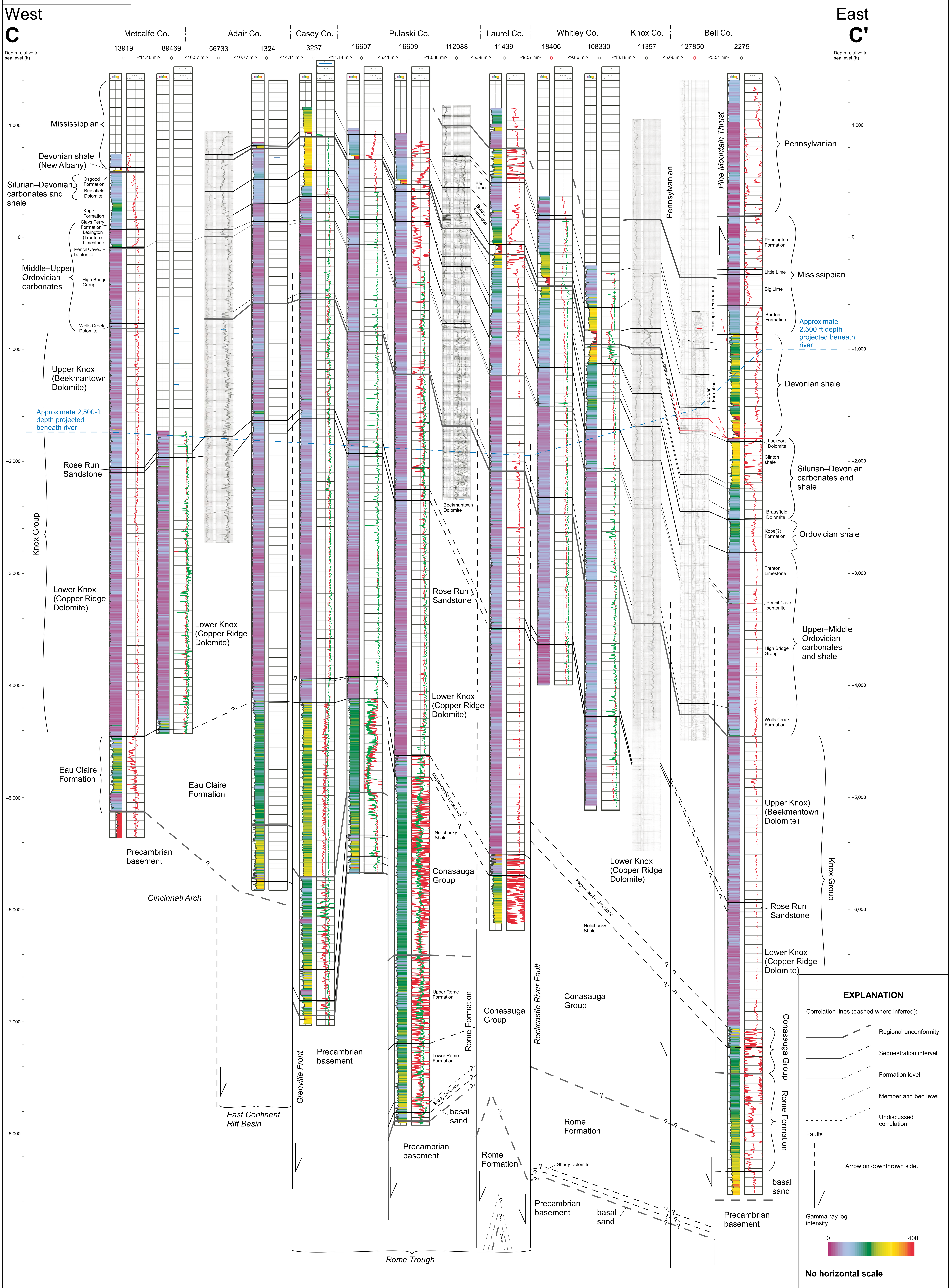
The rock unit intervals correlated in this cross section are described in the accompanying report. Correlations represent interpretations of approximate depths and thicknesses of the units based on available data. Actual depths and thicknesses may vary, especially in faulted areas. It is also important to understand that an interval described as a potential saline reservoir will not have characteristics that allow injection and carbon storage across the entire thickness shown. Potential storage will only be possible in much smaller zones of those intervals, as discussed in the accompanying report.

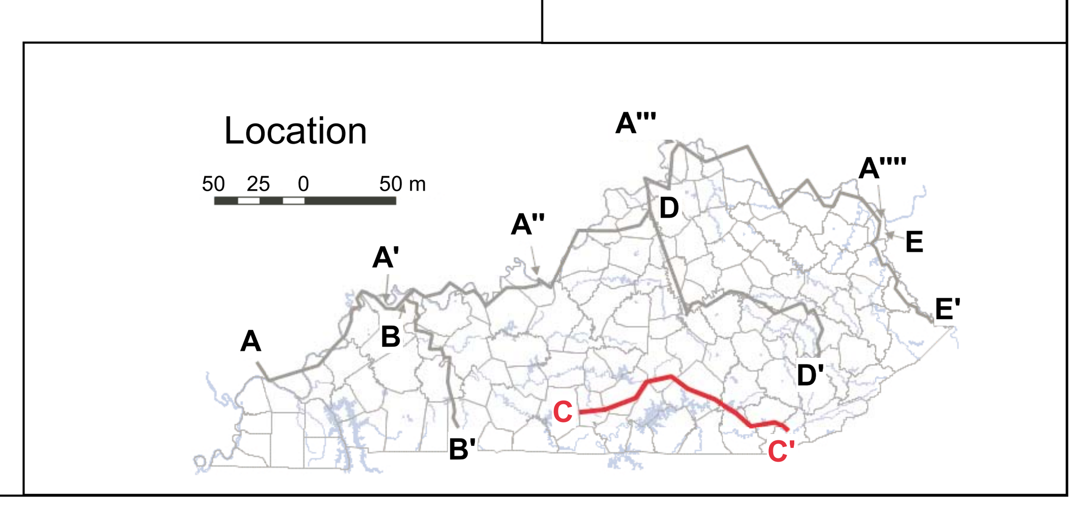
Plate 4.5.
Green River cross section
Chapter 4: Geologic Carbon Storage (Sequestration) Potential in Kentucky

The rock unit intervals correlated in this cross section are described in the accompanying report. Correlations represent interpretations of approximate depths and thicknesses of the units based on available data. Actual depths and thicknesses may vary, especially in faulted areas. It is also important to understand that an interval described as a potential saline reservoir will not have characteristics that allow injection and carbon storage across the entire thickness shown. Potential storage will only be possible in much smaller zones of those intervals, as discussed in the accompanying report.

Plate 4.6.

Cumberland River cross section.
Chapter 4: Geologic Carbon Storage (Sequestration) Potential in Kentucky

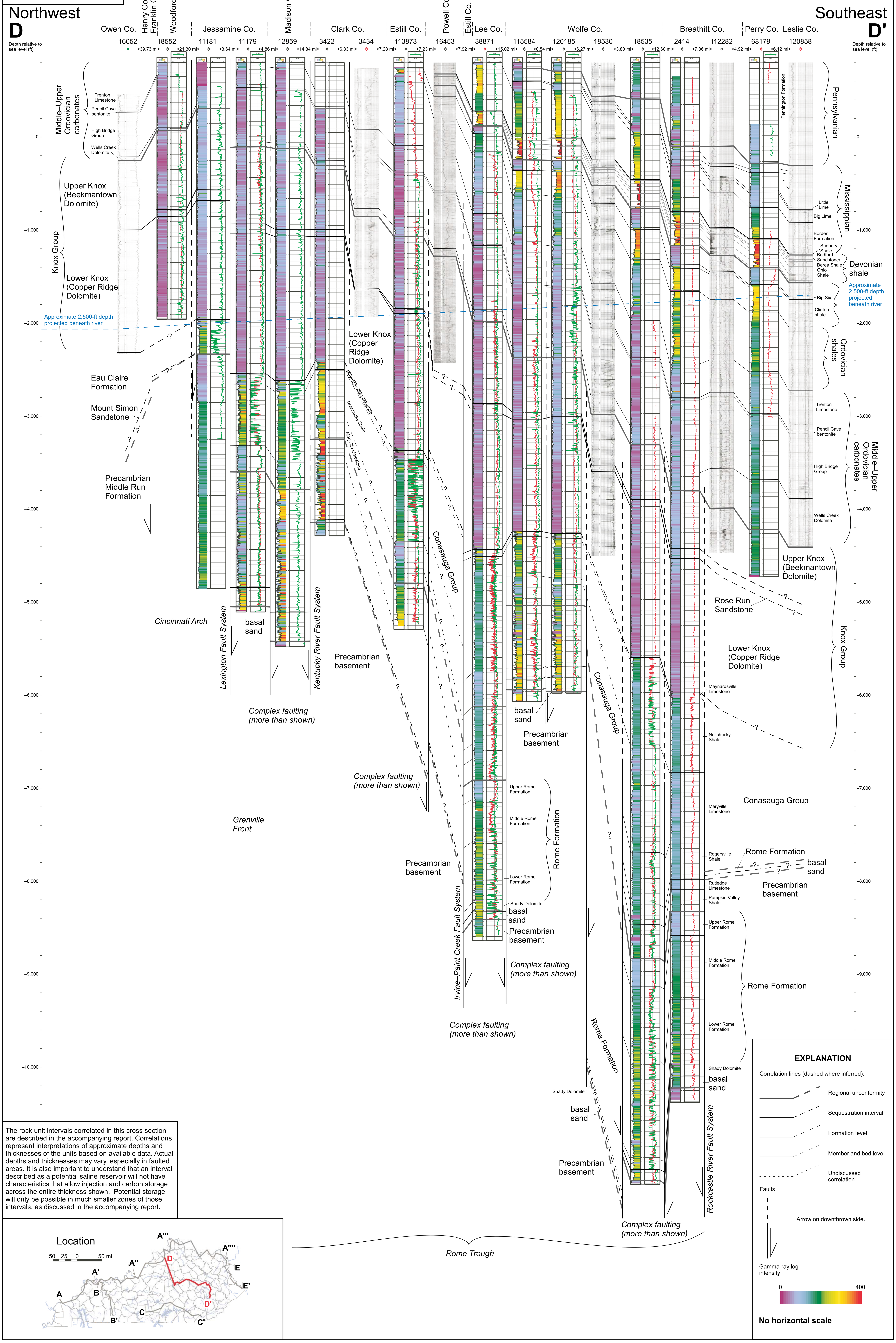




The rock unit intervals correlated in this cross section are described in the accompanying report. Correlations represent interpretations of approximate depths and thicknesses of the units based on available data. Actual depths and thicknesses may vary, especially in faulted areas. It is also important to understand that an interval described as a potential saline reservoir will not have characteristics that allow injection and carbon storage across the entire thickness shown. Potential storage will only be possible in much smaller zones of those intervals, as discussed in the accompanying report.

Plate 4.7.

Kentucky River cross section.
Chapter 4: Geologic Carbon Storage (Sequestration) Potential in Kentucky



The rock unit intervals correlated in this cross section are described in the accompanying report. Correlations represent interpretations of approximate depths and thicknesses of the units based on available data. Actual depths and thicknesses may vary, especially in faulted areas. It is also important to understand that an interval described as a potential saline reservoir will not have characteristics that allow injection and carbon storage across the entire thickness shown. Potential storage will only be possible in much smaller zones of those intervals, as discussed in the accompanying report.

Plate 4.8.

Tug Fork cross section.
Chapter 4: Geologic Carbon Storage (Sequestration) Potential in Kentucky

The rock unit intervals correlated in this cross section are described in the accompanying report. Correlations represent interpretations of approximate depths and thicknesses of the units based on available data. Actual depths and thicknesses may vary, especially in faulted areas. It is also important to understand that an interval described as a potential saline reservoir will not have characteristics that allow injection and carbon storage across the entire thickness shown. Potential storage will only be possible in much smaller zones of those intervals, as discussed in the accompanying report.

KENTUCKY GEOLOGICAL SURVEY
James C. Cobb, State Geologist and Director
University of Kentucky, Lexington

Map of Reflection Seismic Data in Kentucky

In assessing the geologic storage potential for carbon dioxide in any particular area of Kentucky, as complete a picture as possible of the subsurface geology is essential. Often deep-well data is not sufficiently dense to provide the necessary information. In such cases, regional reflection seismic data may supplement otherwise sparse drill data. Many areas have data that was previously acquired, usually by oil and gas exploration companies. Reflection seismic data may be difficult to find, especially by those users unfamiliar with oil and gas exploration.

The map of the reflection seismic data in Kentucky is intended to provide users with a quick visual reference that will allow them to determine the particular areas of the state that have seismic data and the identity of the data owner or primary source for the specific data. All other information concerning the seismic data are within the purview and available from the data owners, primary providers, or vendors, as the case may be. These primary sources are listed below for any particular survey shown on the map.

In addition to existing data, two seismic surveys in progress are shown on the map. These are the surveys being conducted by the Kentucky Geological Survey (KGS) in Hancock County and a group shoot by Evans Geophysical, Inc. (Evans) in eastern Kentucky.

The location of the seismic data on the map is the information supplied directly by the various primary sources listed below. In most cases, the data was supplied as digital data in ESRI shapefile format. The exception is the existing Evans Geophysical, Inc. data that was supplied as paper copies of page-size stick or shot-point maps (the proposed Evans group-shoot data, however, was provided in digital shapefile format). In the case of the Evans paper copies, the lines or points located as closely as possible using roads, county lines, or Carter Coordinate sections for geographic control. It is likely, therefore, that these lines may lack the location accuracy of the other lines on the map.

The map is a work in progress and is intended to be complete as possible; however it is known that some of the data available in Kentucky may not shown on the map as detailed location information concerning certain surveys is not currently available from the owners. For example in southeastern Kentucky, Seisco has additional seismic data not shown on this map. When in doubt, users of this map should consult vendors about the possibilities of additional data. If publicly available data are found that are not shown on this map, the authors would welcome notification to aid in updating future versions of the map.

For the past 40 or more years, reflection seismic data have been collected in Kentucky by the oil and gas industry and less commonly by governmental agencies. During this time, major oil companies including Amoco, Arco, Conoco, Exxon, Gulf, Shell, Texaco, and geophysical companies like Petty Ray, Western Geophysical, and Texas Instruments Geophysical Service, Inc. collected regional seismic data. In addition, smaller exploration companies including Ashland, Columbia Natural Gas, and others collected data limited to specific areas. By the 1980s most of the major companies had ceased hydrocarbon exploration operations in Kentucky and by the late 1990s most had made their seismic data available through outside vendors. More recently, seismic data have been collected by state government and private agencies for the purpose of deep-well disposal operations (Ohio Geological Survey) and carbon storage (Battelle).

Additional seismic data is currently being collected by the Kentucky Geological Survey in Hancock County in preparation for the drilling of an 8,000-foot test well that will test Lower Paleozoic strata for their suitability as reservoirs and seals for carbon dioxide storage. It is expected that additional seismic data may be collected in the future for carbon storage purposes in response to the incentives related to coal-to-liquids legislation (House Bill No. 1) passed by the Kentucky Legislature in August 2007.

Seismic data continues to be collected for oil and gas purposes. Evans Geophysical, Inc. is collecting data as part of a group shoot in eastern Kentucky across the Rome Trough and that proposed survey has been included on the map. The details of the group shoot being proposed by Seismic Specialists, Inc. across the Rough Creek Graben in western Kentucky are unknown at this point and are not shown on the map.

To date, all of the known data collected in the state is considered two dimensional (2-D), that is, it reflects only the subsurface geology lying directly below the line of survey and does not result in a data volume as is the case with three-dimensional (3-D) data. Much of the reflection seismic data collected in the state are multifold in nature, that is, multiple records are collected from the same subsurface reflection point to build up a clearer, more noise-free and more complete subsurface image. Single-fold data, on the other hand, collects only one record per subsurface reflection point to produce a noisier and less complete image of the subsurface by producing gaps in the shallow data. However, because of the long offsets used in acquiring the data, the deeper geology below about 1,500-2,500 feet is often well imaged. In general, the single-fold data are older and most are confined to the eastern part of the state where they are often the only data available. The data density is much greater in eastern Kentucky, where most of the passable roads have had one or more surveys conducted along them. Western Kentucky, on the other hand, generally has long, regional and broadly spaced surveys that are commonly somewhat newer and with greater fold, resulting in higher resolution.

For many years the GeoData Corporation provided legacy seismic data to users in Kentucky and an index map entitled, "Kentucky-Tennessee Seismic Data" was provided to potential data purchasers. GeoData is no longer in business and the much of the seismic data shown on that map are not available, with some of it being owned by private companies. Other GeoData data, however, are available through the vendors listed herein (personal communication, Ben Rummerfield, 2008).

ExxonMobil Corporation is also known to have shot seismic data in Kentucky; however, their multifold data are available only if the potential purchaser is willing to pay for the time required by ExxonMobil employees to retrieve the data. ExxonMobil multifold seismic data exist for parts of western Kentucky, especially in the area of the Rough Creek Graben where Exxon drilled wells. Some of the single-fold Exxon data shot in eastern Kentucky are available through the vendors listed below.

The seismic data map is color coded to match with the data with the owner or source given below. Some of the companies listed are also data brokers and may be available to help acquire most of the seismic data.

Battelle Memorial Institute (Battelle)
505 King Ave.
Columbus, Ohio 43201-2693
Tel: 800-201-2011 or 614-424-6424
www.battelle.org/locations/columbus.aspx

Evans Geophysical, Inc. (Evans)
2340 S. Mission View
Suttons Bay, Michigan 49682
Tel: 231-271-6296
www.evansgeo.com

Kentucky Geological Survey
228 MMRB
University of Kentucky
Lexington, Kentucky 40505-0107
Tel: 859-257-5500
Fax: 859-257-1147
Public Information Center: 859-257-3896
www.uky.edu/KGS

Ohio Division of Geological Survey (Ohio Geological Survey)
2045 Morse Rd., Bldg. C
Columbus, Ohio 43229
Attn: Mark Baranoski
Tel: 614-265-6586
Fax: 614-447-1918
Mark.Baranoski@dnr.state.oh.us
www.dnr.state.oh.us/Default.aspx?alias=www.dnr.state.oh.us/geosurvey

PAC Geophysical (PAC)
Houston, Texas
Tel: 281- 293-0293 Phone
Fax: 281-293-7899 Fax
Email: pacgeo@aol.com
www.3dsurveys.com

Seisco, Inc. (Seisco)
5701 Crawford St., Suite H
New Orleans, Louisiana 70123
Tel: 504-731-2995
Fax: 504-731-2997
www.seiscoinc.com/

Seismic Exchange, Inc. (SEI)
11050 Capital Park Drive
Houston, Texas 77041
Tel: 832-590-5100 / 866-761-5609 (Toll Free)
Fax: 832-590-5290 (Main)
www.seismicexchange.com

Seismic Specialists, Inc. (SSI)
1680 Hoyt Street
Lakewood, Colorado 80215
Tel: 281-799-5442
Email: paul@shearwave.com
www.shearwave.com

Seitel, Inc. (Seitel)
10811 South Westview Cir. Dr.
Suite 100 Building C
Houston, Texas 77043
Tel: 832-295-8300
Fax: 832-295-8301
www.seitel-inc.com

Texas Gas Transmission, LLC (TGT)
3800 Frederica St.
P.O. Box 20008
Owensboro, Kentucky 42304-008
Tel: 270-926-8686
www.txgt.com

Wilson Geophysical, Inc. (Wilson)
Attn: Bart Wilson, Sales
11011 Richmond Ave., Ste. 225
Houston, Texas 77042
Tel: 713-977-4900
Cell: 832-731-7468
Fax: 713-977-4903
bwilson@wilsongeophysical.com
www.wilsongeophysical.com

MAP OF REFLECTION SEISMIC DATA IN KENTUCKY

by
James A. Drahovzal and Thomas N. Sparks

DISCLAIMER

Although these data have been processed successfully on a computer system at the Kentucky Geological Survey (KGS), no warranty, expressed or implied, is made by KGS regarding the utility of the data on any other system, nor shall the act of distribution constitute any such warranty.

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Projection: Kentucky Single Zone, NAD1983, State Plane Kentucky, FIPS 1600, Feet